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Astronomy: Stars, Galaxies, and the Universe

Course Guide

Professor James B. Kaler

University of Illinois at Urbana-Champaign

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Course Syllabus

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Photo courtesy of James B. Kaler

About Your Professor

James B. Kaler

James B. Kaler is Professor Emeritus of Astronomy at the University of Illinois at Urbana-Champaign. He received his bachelor of arts degree in astronomy from the University of Michigan in 1960 and his PhD from UCLA in 1964. He has held both Fulbright and Guggenheim Fellowships, and has been awarded medals for his work from the University of Liége, in Belgium, and from the University of Mexico. He currently serves on the board of directors of the Astronomical Society of the Pacific.

Long interested in science popularization, Professor Kaler has written for a variety of magazines that include *Astronomy*, *Sky and Telescope*, *Stardate*, *Scientific American*, the Italian magazine *l'Astronomia*, and the Dutch magazine *Zenit*. He was also a consultant for Time-Life Books on its "Voyage Through the Universe" series, and appears frequently on various radio programs and on regional Illinois television. Professor Kaler has written several books that include three for Cambridge University Press, two for Copernicus Books, a pair of textbooks, and another pair for the prestigious *Scientific American* Library series, one of only three scientists to have done so. His work has been widely hailed: *Stars and Their Spectra* (Cambridge) was selected by *Sky and Telescope* as one of the astronomy books to bring to a desert island; *Choice* called *Stars* (*Scientific American* Library) "an elegantly written book . . . recommended for general readers"; the *Observatory* referred to *The Ever-Changing Sky* as ". . . a notable success . . . a fine book which fills a notable gap in the literature"; *Extreme Stars* was the American Association of Publishers choice for "Outstanding and Scholarly Title in Physics and Astronomy" for 2001.

Long specializing in teaching beginning undergraduate astronomy, Professor Kaler has been cited several times in the university's list of excellent teachers and has won three teaching awards from student groups. Outreach activities include extensive lecturing to the public and to planetarium groups, and a suite of popular and award-winning websites that include "Skylights" (a weekly column on what's up in the sky at www.astro.uiuc.edu/~kaler/skylights.html) and "Stars" (which highlights a star of the week, with labeled photographs, at www.astro.uiuc.edu/~kaler/sow/sow.html). A planetarium show based on his life and work (*The StarGazer*) is playing in small planetaria around the world. Professor Kaler's outreach activities were honored by the University of Illinois with the "Campus Award for Excellence in Public Engagement" for 2003.

On a personal level, Professor Kaler is married with four children, and is blessed with six granddaughters. He likes to cook, run, photograph the beauty of the world, and play the guitar and trumpet. He is also a past president of the board of directors of the Champaign-Urbana Symphony.

Introduction

Even to the unaided eye, the sky displays a richness of sights. Stars of different brightnesses and colors spangle the blackness of night. Here and there are pairs and clusters. If the right time of year, a band of white encircles the heavens, the Milky Way, bejewelled with bright stars and stamped with mysterious voids. Binoculars and small telescopes reveal more: the Milky Way is made of countless faint stars, while double stars, clusters, and clouds of swirling gas abound.

Powerful telescopes that span the spectrum of radiation, both on the ground and flying above the Earth's atmosphere, have broken open much of the mystery of the starry sky, while at the same time enhancing its beauty. We know the Milky Way is the manifestation of our disk-shaped Galaxy of some 200 billion stars, and that its dark clouds are the stars' hidden birthplaces. From there we can trace the flow of their lives to their deaths as burnt cinders or in powerful explosions that leave behind some of the most bizarre characters to be found anywhere.

Over the past century, our vision has taken us far beyond the home Galaxy into the vastness of the Universe, where we find we are hardly alone. As far as we can see are countless other galaxies of all shapes and sizes set within an ever-expanding space that was created in a "Big Bang" nearly 14 billion years ago.

Along with solutions to old puzzles, however, come new riddles, as most of our Universe appears to be in the form of some kind of unseen "dark matter" and incomprehensible "dark energy" whose natures and origins remain unfathomable. Yet with all our questions—and knowing that there are questions still to be asked—we have learned the most important lesson: that all of this Universe is our home, that it took all of it to make us, that it is ours to behold and enjoy.

Come then on a voyage that begins with our very own star, the Sun. Along the way we will visit the births, lives, and deaths of stars, explore their circling planets, their groups and galaxies, and all the stuff in the spaces between them. We finally launch ourselves deep into the cosmos to witness the birth of it all, and in returning ride the light waves from the dawn of time right back to Earth.

While this course stands on its own, it is also an ideal complement to the first course of the set (Astronomy: Earth, Sky, and Planets), which covers celestial motions, constellations, telescopes, and planetary astronomy, all of it then integrated into a full picture of space and time.

Lecture 1:
The Neighborhood

Before beginning this lecture you may want to . . .

Read Chapter 1 of James Kaler's *Astronomy! A Brief Edition*.

Introduction:

We look outward from our home, Earth and Solar System, into deep space, peering progressively farther and farther, to the Sun and stars, and then past them to the distant galaxies and the earliest glimmers of the formation of the Universe. But first we must assess our own neighborhood so that we can make sense of how we finally fit into it all.

Consider this . . .

1. Where are we in the grand scheme?
2. How do the local things, like the planets, relate to the stars?
3. How do things work to keep it all together?

A. **Context**

The Universe is . . . no other word for it . . . vast. By definition, it encompasses EVERYTHING. You look out at it at night, and it is all jammed together, the Moon, planets, galaxies, all on the face of the sky. In reality, the distances are unreachable to the human mind. While we can give names to these distances and apply the numbers, no one of us really knows what they truly mean. In this course, we look at "outer space," at the "great beyond" of the stars, at what made them, at where they go when they die, at how they are organized into grand systems, and how these systems are themselves organized into the great mural of the Universe. None of the "big," however, makes any sense without the examination of the small, without looking at our own home, at our tiny planets that orbit our modest Sun, which will shortly be the stepping stone to the stars and to the expanse beyond.

B. **Sun and Planets**

1. Our Solar System holds a great number of things, first the Sun itself, a star that is kept "alive" through "thermonuclear fusion," the conversion of dominant hydrogen in its deep core into helium with the release of energy.
2. The Sun is orbited by nine planets, the Earth being the third one out. Distances in the Solar System (as well as throughout the Universe) are based on the average distance between the Earth and Sun, called the "Astronomical Unit," or "AU," which equals 150 million kilometers (93 million miles). In order outward, with their distances in AU, are Mercury (0.39), Venus (0.72), Earth (1.0), Mars (1.52), Jupiter (5.2), Saturn (9.5), Uranus (19.2), Neptune (30.1), and Pluto (39.4).

© Jim Kaler

Watery planet Earth, warmed by our star, the Sun

3. The spaces between the planets are HUGE compared with their dimensions. While the Sun is 0.01 AU across, the Earth (1/100 the solar diameter) is a mere 1/10,000 AU across. Even Jupiter, the biggest of all the planets, 11 times Earth's diameter, is only 1/10 the solar size. Masses (which relate to the total amount of matter in the body) are equally small. Jupiter has only 1/1000 the solar mass, while Earth has 1/300,000.

4. The planets neatly divide into four sets. The inner four are made of rock with metal cores (the inner five if you include Earth's Moon, the smallest of them, only a quarter of Earth's diameter). The next two (Jupiter and Saturn) are—like the Sun—made mostly of hydrogen and helium with a tiny admixture of all the other chemical elements. Uranus and Neptune are in the middle, with a lot of "rock and ice" (in weird forms) and less of light hydrogen and helium. At the end is Pluto, which fills its own planetary bin . . . except for the large moon of Neptune, which is its clone, and a vast number of other bodies that both share its orbit space and lie beyond it.

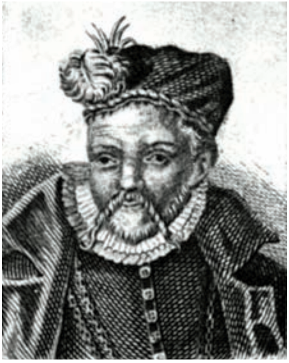
© NASA

Jupiter, the largest of our planets, is a ball of liquid hydrogen and gaseous helium topped by swirling ammonia clouds.

5. All the planets orbit the Sun in the same direction, taking periods that increase outward, from Mercury (88 days) through Earth (365 days) and Jupiter (12 years) to Pluto (238 years). The symmetries—which include consistent ages garnered from techniques involving radioactive elements—all show that everything was made at one time 4.5 billion years ago.

C. **How It Works**

1. Four forces of nature pretty much run things. Of them all, gravity, the one we know best, is by FAR the weakest. It is, however, un-neutralizable (there is no antigravity), and also extends over all space. It is the "glue" that holds us all together. (The others, which we will encounter later, are the "weak force" that involves radioactivity, electromagnetism, and the "strong force" that holds atomic nuclei together.)
2. Gravity was not discovered by Isaac Newton, the great mathematical thinker of the late 1600s. He did something much grander, he de-mystified it by describing how it works and by showing that it is the force that makes one body orbit another. Moreover, he formulated laws of motion and invented calculus, which allows proper interpretation.
3. Newton's laws of motion basically state that nothing does anything unless a "force" makes it do so. If you move along a straight line, you have a "velocity" given by speed and direction. Any change in that velocity (speed OR direction) is an "acceleration," which requires this "force." The "law of gravity" says first that all bodies attract all other bodies throughout the Universe, and that the force is proportional to the product of two attracting masses and inversely proportional to the squares of the distances between them. It can NEVER go to zero!
4. A planet on its own would go in a straight line. But the force of gravity changes the planet's direction, and keeps it moving around the Sun—or the Moon or a spacecraft around Earth. What the planet is really doing is falling—it just never catches up to the Sun as it is also moving perpendicular to the solar direction.
5. In 1609, as a result of careful observations of planetary positions by Tycho Brahe, Johannes Kepler published two laws (followed 11 years later by a third) that describe planetary motions. Here they are, as elicited by Kepler himself: (1) orbits are ellipses, with the Sun (or other body) at one focus. (The ellipse is defined as the curve for which the sum of the distances from any point upon it to two interior points called "foci" is constant. A planet can therefore change its distance from the Sun.) (2) The line connecting a planet with the Sun sweeps out equal areas in equal times (requiring that the planet changes its speed, moving fastest at "perihelion," where it is closest to the Sun, and slowest at "aphelion," the farthest point).



Tycho Brahe

(3) The squares of the orbital periods of the planets in years equal the cubes of the orbital sizes in AU (where the size is half the long axis of the ellipse—the "semi-major axis," "a"), or $P^2 = a^3$.

6. Newton put Kepler's laws on a theoretical basis. Using his own laws, he re-derived Kepler. (1) Planetary orbits are "conic sections"—slices of a cone—that include not just ellipses, but open-ended curves called hyperbolas. (A body comes in, and it just goes back out, never to return.) (2) Conservation of angular momentum. If there is one important rule, this is it. Swing a rock on a string. Angular momentum is the rock's velocity times its mass times the length of the string. In the absence of an outside force it is constant. Decrease the length of the string, and the rock moves faster—the planet moves closer to the Sun and it speeds up. (3) Bring in the masses. In truth, the orbital period in SECONDS squared equals a constant times the orbital size in METERS cubed divided by the sum of the masses of the orbiting bodies in KILOGRAMS, or $P^2 = (K)a^3/(M_{Sun} + M_{planet})$, which can be generalized to ANY two masses. Kepler got away with it because the planets are so puny compared with the Sun that $(M_{Sun} + M_{planet})$ is effectively a constant. The whole Universe operates under these rules. Yet though we can describe it, no one yet knows what gravity actually IS or how it is made.

Sir Isaac Newton

D. **The Other Stuff**

1. The planets (and Sun) are only a part of the Solar System. Small rocky/metallic asteroids clutter the space between Mars and Jupiter. Some work their way inward to hit us as meteorites.
2. Beyond the orbit of Pluto is a reservoir of comets called the "Kuiper Belt," while surrounding the planetary system in a sphere thousands of AU across is another reservoir, the "Oort Comet Cloud." These bodies are likened to "dirty snowballs"; if one is gravitationally kicked into the inner Solar System, it is melted by sunlight. Sunlight and the "solar wind" (a flow of particles from the Sun) then blow the freed gas and dust backwards to create the comet's long tail. The planets were assembled from such bodies, which are now just the leftovers.

E. **The Distant Stars**

1. Stars are most easily defined as gaseous bodies that at some time in their lives shine (or will shine) via thermonuclear fusion (the conversion of lighter chemical elements into heavier ones with the release of energy).

2. The stars are vastly more distant than the planets. If the AU spans a mere inch (2.5 cm), the Sun would be a mote a hundredth of an inch (0.25 mm) across. At a distance of 278,000 AU, the nearest naked-eye star would then be another mote (actually two motes, since it is double) 4 miles (6.5 km) away. A better unit is the "light year," the distance light travels in a year at 186,000 miles (300,000 km) per second, equivalent to 63,200 AU. Stars range from the closest at four light years into the thousands and beyond. That they can be seen over such distances is testimony to the huge stellar radiant power.
3. No two stars are quite alike. They range in size from that of a small town to nearly the orbit of Saturn, from invisible to the eye with any telescope at all to millions of times the solar luminosity, from temperatures not much greater than that of a self-cleaning oven to a million Celsius, all as a result of masses that range from not much more massive than big planets to over 100 times the solar mass combined with the stellar aging process that takes stars from birth to death.

F. **Galaxies and the Universe**

1. Stars are arranged in "galaxies" that have an equivalent range in size and mass. Our Galaxy is shaped like a disk roughly 100,000 light years across, our Sun set out a half to two-thirds of the way to the ill-defined edge. Containing over 200 billion stars, the disk of the Galaxy is seen as the Milky Way. Stars are born from cold gas and dust that lie in the spaces between them, an "interstellar medium."
2. Other galaxies flock around us. Largely arranged in groups and clusters, they span the distances as far as we can see, a trillion of them unto billions of light years away, each with billions of stars.
3. With the exception of a few nearby galaxies, all are receding away from us (and unless bound by gravity into groups, away from each other) at speeds directly proportional to their separations. The conclusion, borne out by a vast amount of data, is that the "expanding Universe" that we see was born out of a hot dense state in a "Big Bang" that took place nearly 14 billion years ago and that is still going on.
4. Deep mystery remains. Stars and other concentrations of "normal matter" constitute less than a quarter of the mass of the Universe derived from gravitational (and other) considerations, the nature of this "dark matter" a complete mystery. The observed acceleration of the Universe's expansion seems to require a "dark energy" that is equally mysterious.

G. **Universe and Earth**

The Earth is not isolated, but is the creation of the Universe as a whole. Its birth five billion years ago was the result of Galactic processes, its matter created largely in the cauldron of exploding stars that spewed heavy chemical elements into the cosmos. We are the children of the stars . . .

FOR GREATER UNDERSTANDING

Questions

1. If you were to construct a scale model of the Solar System, where would the nearest star be?
2. How does gravity keep a planet (or any other body) in orbit?
3. Ponder the hierarchy of things, from the Earth to the Universe at large.

Suggested Reading

Kaler, James. *Astronomy! A Brief Edition*. New York: Addision-Wesley, 1987.

Other Books of Interest

Beatty, J.K., Petersen, C.C., and Chaikin, A., eds. *The New Solar System*. Cambridge MA: Sky Publishing Corp and Cambridge England, Cambridge University Press, fourth ed., 1999.

Ferris, Timothy. *Galaxies*. New York: Random House, 1988.

Morrison, D. *Exploring Planetary Worlds*. Scientific American Library, New York: Freeman, 1993.

Nicolson, I. *Unfolding Our Universe*. Cambridge: Cambridge University Press, 1999.

Spence, P., ed. *The Universe Revealed*. London: Reed Consumer Books Ltd, 1998.

Websites to Visit

1. http://seds.lpl.arizona.edu/nineplanets/nineplanets/ - general planetary science
2. http://wwwflag.wr.usgs.gov/USGSFlag/Space/wall/ - general planetary science
3. http://pds.jpl.nasa.gov/planets/ - general planetary science
4. http://www-astronomy.mps.ohio-state.edu/~pogge/Ast161/Unit4/gravity.html - gravity
5. http://www.astro.uiuc.edu/~kaler/sow/sow.html - stars
6. http://www.seds.org/messier/galaxy.html - galaxies
7. http://www.pbs.org/wnet/hawking/html/home.html - the Universe

Lecture 2:
The Central Sun

Before beginning this lecture you may want to . . .

Read K.R. Lang's *Sun, Earth, and Sky.*

Introduction:

More than just lighting and warming the day, the Sun, the ultimate giver and sustainer of all life, provides nearly all our energy. The comparison to the planets is humbling, the Sun totally dominating the Solar System, the planets merely its satellites that were birthed along with it. The Sun also reaches out to touch us directly with its magnetic fields and wind, the effects on Earth still not all understood or accounted for.

Consider this . . .

1. Are there features, or "things," on the Sun to be seen?
2. What is the Sun made of?
3. What relations does the Sun have with the Earth?

A. **A Warning**

Though the text below may use the phrase "we see" when referring to the Sun, NEVER try to look at it without professionally made and certified filters. The Sun, even while in partial eclipse, is far too bright for the human eye and can cause permanent damage.

B. **Properties**

1. By any scale, solar properties are mind-bending. Some 1.5 million kilometers (93 million miles, the AU) away, the Sun still appears half a degree across in the sky, from which we derive a physical diameter of 1.5 million kilometers (860,000 miles), 1/100 of an AU, or 109 times the diameter of Earth. In volume, the Sun could contain a million of our planet.
2. Newton's more complex generalization of Kepler's third law of planetary motion states that the square of the orbital period of a planet "P" in seconds of time equals a constant times the cube of the orbital size in meters

   divided by the sum of the masses (M) of planet and Sun in kilograms. (Orbital size, "a," is always taken as half the long axis of the elliptical orbit.) That is, $P^2 = \text{const} \times a^3/(M_{Sun} + M_{Earth})$. The only thing not known is the sum of the masses. Since the Earth's mass is minuscule compared with that of the Sun, the sum is effectively M_{Sun}, which comes in at 2 million trillion trillion kilograms.
3. The Sun is gaseous throughout, its apparently sharp edge (or "limb") caused by the gas's high opacity (much like that of the edge of a

cumulus cloud). There are NO solids in the Sun! While the great mass's gravity raises the central density to 12 times that of lead, the consistent high temperature of 16 million degrees Kelvin keeps it gaseous.

4. From the amount of solar radiation that falls on Earth combined with the solar distance, we calculate that the Sun radiates with a power of 200 trillion trillion watts. It would take the gross national product of the United States for millions of years to enable a power company to run the Sun for a second.
5. From the power output of the Sun per unit area, we derive a surface temperature of 5780 degrees Kelvin.
6. Like any other body in space, the Sun rotates, not as a solid body like the Earth, but "differentially." The rotation period is 25 days at the solar equator, but rises to near 30 days toward the poles.

C. **Chemical Composition**

1. The chemistry of the Sun is a fundamental datum that bears not just on the Earth and the Solar System, but that is a test point in our understanding the evolution of the chemical composition of the Universe. The chemical nature of the Sun is divined through the analysis of the absorption lines in the solar spectrum, each of which is related to a particular kind of atom (combined with other information from the "solar wind," the flow of particles from the Sun, and from the spectra of outer solar layers).
2. The Sun is dominated by hydrogen (92 percent by number of atoms) and helium (8 percent). All the rest of the chemical elements fall into a remaining 0.15 percent. Of these, oxygen tops the list, followed by carbon, neon, and nitrogen. Generally, the heavier

LIGHT AND RADIATION

"Light" is but one form of "electromagnetic radiation," which is a flow of energy in the form of alternating waves of electric and magnetic fields that move at the "speed of light," 300,000 kilometers (186,000 miles) per second. The kind of radiation depends on the length of the wave (from crest to crest), the human eye sensitive to waves between four and eight hundred-thousandths of a centimeter. Different wavelengths appear to us as different colors. From long to short, they are red, orange, yellow, green, blue, and violet. Longer waves are called "infrared," and near a wavelength of 1 mm are referred to as "radio." Shorter than human vision lies the "ultraviolet," then the X-ray, then "gamma ray" region, which has wavelengths well under a thousandth that of visual light. Light can also be thought of as a flow of particles called "photons" that in a very loose sense "carry" the waves. These forms of light are the major means by which energy is transmitted in the Universe. The shorter the wavelength, the greater the energy, radio waves mostly benign, infrared felt as "heat," ultraviolet causing burns, X-ray and gamma rays deadly.

the element, the less there is of it, though other patterns emerge, particularly a peak in number at and around iron (rendering iron the most abundant of metals). The chemical composition of the Earth roughly reflects that 0.15 percent, the leavings after the hydrogen and helium have been cooked away.

D. **The Surface and Outer Layers**

1. The surface of the Sun, called the "photosphere" ("sphere of light"), is not smooth, but is made up of over a million bright "granules" divided by dark lanes. The granules are the tops of "convection cells" caused by the bubbling up of hot gas that radiates, cools, and then falls into the dark spaces between, each granule lasting only a few minutes.
2. A thin transparent gas that radiates light from hydrogen, and thus appears reddish—the "chromosphere"—lies above the photosphere. Though the temperature rises upward from the photosphere as a result of magnetic heating, the chromosphere is only visible to the eye during an eclipse of the Sun (when the Moon blocks out the brilliant photosphere) or with specially made filters.
3. The chromosphere is our ticket to the outer solar "corona," a vast envelope of hot, 2-million-degree gas that surrounds the Sun. Far too faint to be seen against the blue sky, the full corona is visible only during a total eclipse or from space.

E. **Magnetism and Solar Activity**

1. Among the most obvious features of the Sun are dark "sunspots" that can be so small as to be just barely visible, or so large as to encompass more than the Earth. With interior temperatures of 4500 Kelvin, they are not black, but just look so by comparison with the photosphere. They are not permanent features, but come and go on a time-scale from days to months.
2. The interior of the Sun is in a state of ionization, in which electrons are stripped from atoms. Motion of this electrified gas as a result of rotation combined with convection produces a magnetic field that is globally roughly the strength of Earth's. The differential rotation concentrates the magnetic field into thick ropes, amplifying it by thousands of times. Convection can bubble a magnetic rope upward, causing it to pop through the solar surface in a loop. Where a loop exits and re-enters the Sun, it in turn inhibits convection and produces a pair of dark spots.
3. The number of sunspots varies with an 11-year cycle. In each hemisphere, the magnetic direction (positive or negative) of the spot that leads in the direction of rotation has the direction of that hemisphere's magnetic pole. The directions remain constant over an 11-year cycle, and then reverse, making the full magnetic cycle 22 years long.
4. Large magnetic loop structures confine the hot gases of the corona. Where they are not confined, the gases stream away from the Sun to create a "solar wind" that causes gaseous comet tails to point away from the Sun and that impacts the magnetic field of the Earth to create bright atmospheric aurorae near the Earth's poles. When a magnetic

loop on the Sun collapses, a portion of confined corona can be ejected. If it hits the Earth, we may see these "northern and southern lights" at lower latitudes. The collapse can also produce brilliant "solar flares" near the solar surface.

5. Between about 1645 and 1715, sunspots (discovered by Galileo around 1610) disappeared, a period called the "Maunder Minimum." At the same time, the Earth was plunged into a cold period, the "little ice age," when deep snows covered northern Europe and the northern plains. From this discovery and other data, it is clear that solar activity affects and heats the Earth, though the reason is not clearly understood. What is understood are the powerful and complex relations that exist between the Earth and the amazing body that keeps our planet warm enough for life to exist.

FOR GREATER UNDERSTANDING

Questions

1. Ponder the meaning of the Sun to us.
2. How does the magnetism of the Sun affect us?
3. What does the solar spectrum tell us?

Suggested Reading

Lang, K.R. *The Cambridge Encyclopedia of the Sun*. Cambridge: Cambridge University Press, 2001.

Other Books of Interest

Golub, L, and Pasachoff, J.M. *The Solar Corona*. Cambridge: Cambridge University Press, 1997.

Lang, K.R. *Sun, Earth, and Sky*. New York: Springer, 1995.

Phillips, Kenneth J.H. *Guide to the Sun*. Cambridge: Cambridge University Press, 1992, 1995.

Websites to Visit

1. http://sohowww.nascom.nasa.gov/ - SOHO spacecraft views of the Sun
2. http://solar.physics.montana.edu/nuggets/index.html - Yohkoh Soft X-Ray Telescope, notes on the Sun
3. http://science.msfc.nasa.gov/ssl/pad/solar/default.htm - general solar physics
4. http://www.bbso.njit.edu/ - Big Bear Solar Observatory

Lecture 3:
The Making of Sunlight

Before beginning this lecture you may want to . . .

Read from K.R. Lang's *Cambridge Encyclopedia of the Sun*.

Introduction:

From Earth we see only the solar skin, a layer of semitransparent gas. Plunge now into deep interior. We know its characteristics through the probe of physical theory, with which we can build a picture of the solar depths and learn that it shines by nuclear fusion, the Sun a controlled "hydrogen bomb." The agreement between outward observation and theoretical prediction reveals that our theories are correct, and shines extra light on the nature of matter itself.

Consider this . . .

1. Where does sunlight come from?
2. How can the Sun stay lit for so long?
3. Will it ever die?

A. **What Makes Sunshine?**

1. The riddle of sunshine is tied to our perception of the Sun's age. If the process were combustion, even of volatile gasoline, the Sun could last for but a few thousand years. The geological record, however, demonstrates the Earth to be far older. In the 19th century, William Thompson (Lord Kelvin) and Hermann von Helmholtz had an answer. If you compress a gas, you heat it. The piston in a diesel engine squeezes an air-fuel mixture. When the temperature hits the burning point, the mixture explodes and drives the piston outward. In the Sun (and other stars), the piston is gravity, whose compression causes the interior of the Sun to heat. A hot gas must radiate, and given the solar conditions will radiate at the solar luminosity. But that by itself would cool the gas, which causes the Sun to shrink some in order to maintain the pressure. The process, called Kelvin-Helmholtz contraction, works fine to explain the Sun's brightness. With an annual shrink-rate of about 20 meters, the Sun could shine for nearly 100 million years.

2. The problem appears solved until we look at the true age of the world, made possible through the discovery of radioactivity. Every unstable radioactive isotope ultimately decays to a stable daughter isotope. Uranium-238, for example, eventually creates lead-206. Most normal lead, however, is lead-208. If we know the decay rate of U-238, the ratio of lead-206 to U-238 within a rock tells the age since solidification. A variety of other isotope ratios are available. The most ancient rocks of Earth are over 3.5 billion years old, while the oldest found on the Moon

(from the Apollo program) have an age of 4.5 billion. The oldest of all are a set of stony meteorites (from the asteroid belt) that come in at 4.56 billion. Since these are the oldest things we can find, that figure is taken as the age of the whole Solar System and the Earth. The Earth just appears younger because as a large body, it took longer to cool and solidify from the heat of creation. The fossil record also shows that the Sun has been radiating at something close to its current level for billions of years. Kelvin-Helmholtz contraction cannot generate the observed luminosity for all the solar age.

3. The British astrophysicist Sir Arthur Eddington, one of the first to understand and accept Einstein's theory of relativity, directed us to the answer. One helium atom weighs 0.7 percent less than four hydrogen atoms (or protons). Einstein showed that mass (M) and energy (E) are related, and can be converted by the famed equation $E = Mc^2$, where c is the speed of light. A small amount of mass can therefore create a huge amount of energy. If hydrogen atoms can combine into helium, the lost mass generates enough energy to keep the Sun going for the required billions of years.

4. The absorptions in the solar spectrum (explored in Lecture 2) are dominated by calcium and other metals, not hydrogen. Celia Gaposhkin, who applied budding atomic theory, showed that once the efficiencies of absorption were taken into account, the Sun and stars are made dominantly of hydrogen. There is plenty of raw material.

B. **Look Inside**

1. The temperature of the Sun does indeed climb with depth below the surface. The apparent solar disk is

ISOTOPES

The nuclei of most chemical elements can take a range in the number of neutrons allowed within them, each called an "isotope" of the element. Normal hydrogen has one proton, making it hydrogen-1. However, you can stick a neutron to the proton to make heavy hydrogen, hydrogen-2, or deuterium, which constitutes about one hydrogen atom in a hundred thousand. Carbon has two isotopes, carbon-12 (6 protons and 6 neutrons) and carbon-13 (6 protons and 7 neutrons). Tin has 10. However, too many or too few neutrons will make the isotope unstable, and it falls apart with the emission of energy in the form of high-speed particles, and radiation, that is, it is "radioactive" and potentially quite dangerous. A second neutron attached to hydrogen makes radioactive hydrogen-3, or tritium. Above bismuth (element 83), ALL isotopes are radioactive, the set including radium and uranium.

brightest in the middle and darkest at the edge, or "limb." The solar "surface" (photosphere) is partially transparent

and has a depth into which we can see a thousand kilometers or so. Though the Sun appears as a disk in the sky, it is really a sphere. When we look into the gases at the limb, our view extends along the same length of path that it does at the center, but because at the limb we look in at an angle, we do not see as deeply. Since the temperature climbs inward, our view of the limb is through lower temperatures. The solar limb is therefore less bright, and also redder, than the solar disk's center. Theory shows that a steady temperature increase must be maintained all the way to the center of the Sun itself. There, we calculate a temperature of 16 million Kelvin and a density of 150 grams per cubic centimeter, over a dozen times that of lead. And it is still a gas.

2. The granulation of the surface (that it is covered with over a million bright patches separated by dark lanes) demonstrates that the outer part of the Sun is in a state of convection, in which hot gases rise, radiate, cool, and fall back inward. Theory shows that the outer third of the Sun is unstable against such convective motion, creating the solar "convective envelope." The inner two-thirds does not undergo convection and is divided into a "radiative envelope" and a "core" that occupies about 30 percent of the radius and 40 percent of the mass, where the conditions are right for the required nuclear reactions to take place.
3. Oscillations in the Sun, that it vibrates like a bell, allow us to probe deep inside and to construct an "image" of the solar interior, which entirely supports theory.

C. **Thermonuclear Fusion**

1. Knowledge of the process required a number of other discoveries that included that of the neutron, of the strong force that binds nuclei together, and of the wave-behavior of subatomic particles. Since protons have similar (positive) electric charges, they must naturally repel one another. To get them to stick via the strong force (which acts over only the radius of the proton), they must be brought very close together. Atoms move within a gas, their velocities dependent on temperature. However, at any temperature, the constant collisions among them also create a great range in velocity. Some will be barely moving. There will then be a sort of "average" velocity with which the majority of atoms will be moving. Finally, there will be a long tail of extremely fast-moving particles. At high enough temperatures, this last set will have enough velocity that when they collide they can overcome the barrier produced by the repulsive charge and can get the protons close enough to stick. Even this effect is not quite enough. Since protons behave like waves, however, they can "jump" in position, which allows them, once they are close enough together, to "tunnel" right through the electrical barrier rather than having to "climb over it." The result is that a temperature of roughly five million Kelvin (given the appropriate high-density conditions of the solar interior) is sufficient to begin to allow the reactions to proceed. Such conditions are thoroughly met in the solar core.

2. Most of the solar energy is generated in a three-step thermonuclear fusion process called the “proton-proton chain.” A fast moving proton meets another proton, and they momentarily stick. Even the strong force, however, is not enough to keep them together. But at the same instant, one of the protons loses its positive charge (by means of another force of nature called the “weak force”) to become a neutron (which also carries the strong force), allowing the two to remain bound together as a heavy isotope of hydrogen, hydrogen-2, which goes by the special name of deuterium. The positive charge flies away as a positive electron, a “positron” (an example of “antimatter”), which does not get very far before it encounters a normal negative electron. The two then annihilate each other in a burst of two high-energy gamma rays. Accompanying the ejection of the positron is a near-massless particle of the weak force called a “neutrino,” which also carries energy. The deuterium atom quickly encounters another proton, whose addition makes light helium, helium-3, and another gamma ray. Finally, two helium-3 atoms mate to create normal helium-4, in the process ejecting two protons.

3. The lost mass, which first appears as energy in the form of gamma rays, slowly works its way out of the Sun. A newly made gamma ray will not get far before it is absorbed by an ion of some sort. It is then re-emitted, reabsorbed, re-emitted, and so on. But because the Sun’s temperature drops outwardly, on the average each time the photon is emitted a bit farther from the center, where it is cooler. The total energy must be the same, so the re-emissions on the whole consist of more and more of lower and lower energy photons. After a million or so years, the energy makes its way to the solar surface, where each gamma ray made in the core is radiated as thousands of visual photons, giving the Sun a soft yellow-white light.

4. A variety of other reactions go on in the core as well, including several “side chains” that involve somewhat heavier elements, and a low level of the “carbon cycle,” in which carbon is used as a nuclear catalyst to bind four atoms of hydrogen into one of helium with the creation of various isotopes of nitrogen and oxygen (the carbon cycle is crucial in running stars substantially more massive than the Sun).

5. Thermonuclear fusion of hydrogen (“hydrogen-burning” in the vernacular) does not vitiate Kelvin-Helmholtz contraction. It is the solar contraction, the binding of the Sun through its own gravity, that boosts the interior temperature high enough for the nuclear reactions to take place. Given its core hydrogen-burning, the Sun does not need contraction to “stay alive,” so gravity is held at bay. There was enough hydrogen in the early core to keep the Sun going for 10 billion years. We are half-way done, at which point gravity will again take over, and the Sun will begin to die.

6. As weak force particles, neutrinos do not readily react with matter, and escape the Sun directly. Most pass right through the Earth, billions of them going through you each second. Neutrino “telescopes,” buried deep in the ground to exclude other particles, rely on rare nuclear or other reactions between neutrinos and normal matter. Early neutrino telescopes found a severe shortfall in the numbers coming out of the

solar center, which led to the discovery that the particles have a small amount of mass and can switch from observable to unobservable states, which in turn led to a revision in particle physics, which had predicted zero mass. With modern equipment, neutrinos are indeed seen to pour out of the core of the Sun in the right numbers, fully supporting theory, revealing the Sun to be a natural, stable, nuclear engine.

FOR GREATER UNDERSTANDING

Questions

1. How do the various forces of nature conspire to run the Sun?
2. Summarize the evidence that the Sun really does run off thermonuclear fusion.
3. How do neutrinos play into the solar picture?

Suggested Reading

Lang, K.R. *The Cambridge Encyclopedia of the Sun*. Cambridge: Cambridge University Press, 2001.

Other Books of Interest

Golub, L., and Pasachoff, J. *Nearest Star*. Cambridge, MA: Harvard University Press, 2001.

Lang, K.R. *Sun, Earth, and Sky*. New York: Springer, 1995.

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Websites to Visit

1. http://science.msfc.nasa.gov/ssl/pad/solar/interior.htm - solar interior
2. http://spacescience.spaceref.com/ssl/pad/solar/interior.htm - solar interior
3. http://www.sns.ias.edu/~jnb/Papers/Popular/snhistory.html - solar neutrinos
4. http://zebu.uoregon.edu/~soper/Sun/solarneutrinos.html - solar neutrinos
5. http://www.sno.phy.queensu.ca/ - Sudbury neutrino detector

Lecture 4: Billions of Stars

Before beginning this lecture you may want to . . .

Read James Kaler's *Stars and Their Spectra.*

Introduction:

The Sun is but one anonymous star within a Galaxy of hundreds of billions of them. Though the stars can be considered "other suns," their range of properties is spectacularly large. The Sun, with properties in the middle of all ranges, provides a wonderful benchmark with which to understand them, while the stars, with their immense differences from one another, in turn provide a way to understand the Sun, its origin and fate, and the origin and fate of our very selves.

Consider this . . .

1. How many stars are there?
2. How are they like the Sun, and how might they be different from the Sun?
3. How do they relate to each other?

A. **Observed Properties**

1. The most important thing is distance. Extend a finger perpendicular to your line of sight. Look at it first with one eye and then with the other, and see it jump back and forth against the background. The closer it is, the greater the angle through which it jumps. The same effect is seen in looking at a nearby star from one part of the Earth's orbit and then six months later from another part. The different positions will make the nearby star appear to shift back and forth against the background of distant stars. From the angle of shift, the "parallax," we calculate how far away the star is. Parallax angles are tiny, a fraction of a second of arc at best (a "second" a 60th of a "minute," which is a 60th of a degree, 360 degrees in the circle).
2. Distances are so great that Astronomical Units do not work well. Instead, use the "light year," the distance light travels in a year of 31 million seconds, going at 300,000 km/s, which amounts to 9.5 trillion kilometers (5.9 trillion miles), or 63,200 AU. The nearest star is 4.4 light years away (278,000 AU). Most naked-eye stars are 10 to 1000 light years distant (the practical limit to parallax measure), some much farther. Given that a star, like the Sun, is only 0.01 AU across, stars are typically separated (in our part of the Galaxy) by 30 million times their diameters.
3. Stars cannot be fixed in space, as gravity would draw them together and we could not exist. All stars orbit the center of our Galaxy on slightly different paths, and as a result they slowly drift past one another. The angular

motion of a star across the sky, its "proper motion," is easily measured and depends on distance and actual velocity across the line of sight (which can then be found from proper motion and distance). The velocity toward or away from Earth is found by the Doppler effect. The combination of velocities gives the true stellar motion and the ability to map out the dynamics of the Galaxy, of how things are moving within it. Stellar motions are all too small to be seen with the naked eye over a lifetime; indeed, you see the same constellations (named star patterns) that Homer saw. But over millions of years, they will all dissolve, to be replaced by others.

4. Around 150 BC, the Greek astronomer Hipparchus divided the naked-eye stars into six brightness groups we call "magnitudes," first magnitude the brightest, sixth the faintest. By modern standards, a first magnitude star (1.00) is exactly 100 times brighter than a sixth (6.00), while some brighter stars are forced into negative numbers. With a telescope, you see fainter, 11th magnitude 100 times fainter than sixth, and so on. The limit, viewed with the Hubble Space Telescope, is magnitude 30, four billion times fainter than sixth.

5. The farther away a point of light, the dimmer it appears. The apparent brightness of a star as seen from Earth (the "apparent magnitude") depends on both true luminosity in watts and the distance. To compare stars, astronomers use the distance to calculate "absolute magnitudes," that is, magnitudes the stars would have at a standard distance of 32.6 light years. The absolute magnitude of the Sun is 4.8. The range among all stars is spectacular, from -10 (a million times the solar luminosity) to far below 20 (a million times fainter than the Sun), rendering the Sun in the middle.

B. **The Galaxy**

1. All the stars you see at night, even those seen with telescopes, are part of our Galaxy of 200 or more billion stars. Some 98 percent are arranged in a thin disk roughly 100,000 light years across. Our Sun is set 25,000 light years from the center. The naked eye stars are for the most part just local. The light from the distant part of the disk blends together to form a wide band of starlight called the "Milky Way." Stars in the disk orbit the Galaxy on more or less circular paths, our Sun taking 250 million years to make a full circuit. Velocities of most stars relative to the Sun are typically a few tens of kilometers per second, as found from proper motion, distance, and radial velocity.

2. Surrounding the disk is a vast but sparsely populated "halo." Observation shows that these stars are on looping elliptical orbits. Plowing through the disk, halo stars move at much higher velocities relative to the Sun, up to and over 100 km/s. Other differences will be explored in Lecture 11.

C. **Kinds of Stars**

1. Different kinds of stars are recognized through the absorptions in their spectra. The solar spectrum is dominated by absorption lines of metals, particularly those of calcium and sodium. Hydrogen, while having a

good presence, is relatively weak. The spectra of some stars, however (Vega, Sirius), are entirely dominated by hydrogen, while in others (Betelgeuse, Antares) it is practically absent.

2. The first step in understanding is classification of data. Around 1890 various schemes of spectral classification led to one developed at Harvard in which stars with the strongest hydrogen lines were called class A, next strongest class B, and so on, through much of the alphabet, our Sun class G. Some letters were quickly dropped as superfluous. Astronomers also found that to give other absorptions continuity from one class to the next, it was better if B was placed before A and O before B. The final sequence of seven remaining letters then goes OBAFGKM. This sequence correlates with color, O stars blue-white, M stars reddish, and thus it must also correlate with temperature, as the higher the temperature the bluer the light, the cooler the redder, in accord with standard radiation laws. The sequence goes from around 50,000 Kelvin surface temperature among the hot O stars to 3000 Kelvin in class M. Seven letters are not enough, so the system is decimalized, A0 . . . A9, F0 . . . F9, and so on, the Sun (6000 Kelvin) a G2 star. The spectral class is the most important single thing an astronomer wants to know.
3. In spite of the differences in appearance, the stars of this "spectral sequence" all have about the same chemical composition (like that of the Sun). The sequence is an atomic ionization-excitation sequence caused by changing temperature. At the top, O stars present us with ionized helium, while B stars show neutral helium and hydrogen. Down at the bottom, in class M, the temperature is cool enough to allow abundant fragile molecules, these stars dominated by titanium oxide absorptions.
4. Since hotter bodies are more luminous than cooler ones (the radiative power per unit area going as temperature raised to the fourth power), the temperature of a star ought somehow to correlate to its luminosity. In the early twentieth century, two astronomers, Henry Norris Russell in the United States and Ejnar Hertzsprung in Denmark, began to explore the relation. On the "Hertzsprung-Russell (HR) diagram," temperature is expressed on the lower horizontal axis by spectral class (cooler stars to the right), while luminosity is expressed on the vertical axis (increasing upward) by absolute magnitude. Sure enough, the majority of stars line up from lower right (cool and dim) to upper left (hot and bright). The Sun is smack in the middle of this "main sequence."
5. However, Russell found another branch that starts just above the Sun in which luminosity increases with DECREASING temperature. To be both bright and cool, a star must have a large surface area, that is, it must be BIG. Russell discriminated between the two branches by calling the large stars "giants" and the cooler ones "dwarfs" ("dwarf," no matter what the actual size, synonymous with "main sequence"). The Sun is therefore a G2 dwarf. Hertzsprung found even brighter reddish cool stars, which could then only be called "supergiants." Giants (the classic ones cool and red, and therefore "red giants") can be comparable to the sizes of the orbits of Earth and Mars, while the biggest red

supergiant comes close to that of the orbit of Saturn. The luminary of northern hemisphere winter skies, white-colored Sirius, has a companion of nearly the same temperature (roughly 10,000 Kelvin) but 10,000 times fainter. To be that hot and faint, Sirius B must be small, the size of Earth. Called a “white dwarf” to distinguish it from an ordinary dwarf, it is one of the first of a sequence of white dwarfs that lie rather parallel to, but much fainter than, the main sequence, from hot and blue to cool and red. Since the Sun is a core hydrogen-burning star, by analogy so are the other stars of the main sequence. Giants, supergiants, and white dwarfs must be something else.

6. Most of the naked-eye stars are A and B dwarfs and class K giants that are visible because they are bright. No class M dwarf is visible without a telescope. In truth, over 70 percent of stars are M dwarfs. The numbers drop quickly upward, O dwarfs exceedingly rare.
7. As will be seen in Lecture 5, the masses of stars climb along the main sequence, from a minimum of 0.08 solar at the end of class M to over 100 solar masses among the brightest O stars. Below eight percent the solar mass, the core temperature is not hot enough to support full hydrogen fusion. Lesser stars, called “brown dwarfs,” may extend all the way down to planetary masses, their total number unknown. They are described by classes L (characterized by metallic hydrides) and T (methane). T stars can be no hotter than a self-cleaning oven, are infrared radiators, and are invisible to the eye.
8. Stars can be understood in terms of mass (to which we turn next) and age, the subject of later lectures, all the different kinds beaded on a string of theory.

THE SPECTRAL SEQUENCE

Class	Color	Temperature	General spectral characteristics
O	blue-white	32,000-50,000	Ionized helium, neutral helium and weak hydrogen.
B	blue-white	10,000-30,000	Neutral helium, stronger hydrogen.
A	white	7,200-9,500	Strong hydrogen, increasing ionized calcium.
F	yellow-white	6,000-7,000	Ionized and neutral metals, weaker hydrogen.
G	yellow	5,300-5,900	Ionized calcium, neutral metals strong, hydrogen weaker.
K	orange	4,000-5,200	Strong neutral metals, hydrogen weak.
M	orange-red	2,000-3,900	Strong absorption bands of titanium oxide and large numbers of metallic lines.
L	red-infrared	1,500-2,000	Metallic hydrides and alkali metals.
T	infrared	1,000	Methane bands.

FOR GREATER UNDERSTANDING

Questions

1. Reflect on the stars not as seen on the bowl of the sky, but in three dimensions, all with different distances and motions.
2. List the different kinds of stars.
3. What is the HR diagram, and why is it so important?

Suggested Reading

Kaler, J.B. *Stars and Their Spectra*. Cambridge: Cambridge University Press, 1989, 1997.

Other Books of Interest

Hirshfield, A.W. *Parallax*. New York: Freeman, 2001.

Kaler, J.B. *Extreme Stars*. Cambridge: Cambridge University Press, 2001.

———. *The Hundred Greatest Stars*. New York: Copernicus Books, 2002.

———. *The Little Book of Stars*. New York: Copernicus Books, 2000.

———. *Stars*. Scientific American Library. New York: Freeman, 1998.

Websites to Visit

1. http://www.astro.uiuc.edu/~kaler/sow/sow.html - the star of the week
2. http://www.astro.uiuc.edu/~kaler/sow/star_intro.html - the natures of the stars
3. http://www.astro.uiuc.edu/~kaler/sow/spectra.html - stellar spectra
4. http://www.astro.wisc.edu/~dolan/constellations - more on stars
5. http://www.anzwers.org/free/universe/12lys.html - the nearest stars
6. http://zebu.uoregon.edu/~soper/Stars/hrdiagram.html - the HR diagram
7. http://www.physics.gmu.edu/classinfo/astr103/CourseNotes/ECText/ch17_txt.htm - stellar structure and star birth

Lecture 5:
Ganging Up

Before beginning this lecture you may want to . . .

Read James Kaler's *Stars.*

Introduction:

Stars are organized by position in the sky, giving rise to constellations and a means to name them. They are also organized physically. Most stars come in doubles, triples, multiples, and in clusters, which also contain doubles, triples, and so on. Stellar duplicity is vital in learning about stellar properties, particularly mass, the single most important parameter in the stellar life cycle. Clusters reveal the progress of stellar evolution and allow the calculation of ages, not just of the clusters themselves but of the Galaxy, even of the Universe.

Consider this . . .

1. How are stars organized?
2. How can we get the masses of distant stars?
3. What are these small groups of stars that are visible even to the naked eye?

A. **Organization**

1. The first organization of stars is into apparent groupings, in which (for the most part) stars are unrelated to one another. Randomly distributed, stars naturally fall into a variety of obvious patterns, or "constellations." The figures of the Zodiac, those that hold the planets (which represented the gods), became sacred symbols. Others scattered around the sky were used for storytelling. Forty-eight ancient constellations that represent heros, animals, and objects were passed down by the ancient Greeks. These were supplemented by 38 "modern constellations" that were invented between 1600 and 1800 to fill in the blanks and to populate the deep southern hemisphere that was invisible to ancient northern people. With the breakup of the constellation Argo (the Ship) into three parts, that leaves us with 88 constellations. Other cultures have their own constellation lore.
2. A couple thousand stars have proper, usually descriptive, names. Some are Greek ("Sirius," for "searing"), some Latin, but most are Arabic, assigned by the Arabs following the collapse of the Greco-Roman civilization. Taking on much of the Greek culture and their constellation lore, the Arabs named the stars in accord with position within the Greek, or their own indigenous, constellations. Retranslation into Latin in the middle ages commonly produced terrible corruptions of the original Arabic words and phrases.

3. Proper names are hard to recall, so around 1600 Johannes Bayer assigned Greek letters to the stars within each constellation based on brightness and position, Alpha usually brightest. Vega thus becomes Alpha of Lyra (the Harp), in Latin expressed as Alpha Lyrae. Nearly a century later, John Flamsteed listed accurate positions of stars from west to east within constellations (the first parallax star 61 Cygni).

4. Many catalogues list stars purely by coordinate position. On the apparent sphere of the sky is a coordinate grid much like latitude and longitude on Earth. "Declination" is like latitude, and runs north and south from the celestial equator to the apparent rotation poles, while "right ascension" locates a star to the east of the vernal equinox, the point at which the Sun crosses the equator near March 20th. Millions of stars have precisely measured coordinates, allowing us to know where they are.

B. **Double and Multiple Stars**

1. Well over half the stars in the sky are in double or multiple systems. They can be organized physically or by means of observation. Simple double stars ("binaries") come in a great variety of forms, from those so far apart that they take millions of years to orbit each other and are visible to the naked eye, to those that touch at their surfaces and whirl in hours, from doubles whose stars are nearly identical to those with huge mass, luminosity, and evolutionary (aging) differences. In a hierarchical triple, a third star orbits the double, gravitationally feeling the inner binary as one unit. In a quadruple, two close doubles may orbit each other. A fifth star might then orbit the inner double-double, which may itself be double to make a sextuple. Such hierarchical multiples are stable. Stars in systems like the famed Trapezium that illuminates the Orion Nebula (discussed in Lecture 6) are more or less equidistant and mill about. They are unstable, one star kicking another out of the system until stability is achieved.

2. Observationally, stars are divided into three broad overlapping groups. "Visual binaries" are seen as a pair of stars through the telescope. The traditional separation, the result of turbulence in the Earth's atmosphere (which causes twinkling), is just under a second of arc. A large number of visual binaries are close enough that they orbit within a short enough time for us to find the period, P. If we plot the orbit of the fainter star ("B") about the other ("A") and also know the distance, we can find the orbital semi-major axis. Put in solar units, Kepler's third generalized law can be written as period (years) squared = semi-major axis (AU) cubed, divided by the sum of the masses (in solar masses), the constant dropping out, or $P^2 = \frac{a^3}{M_A + M_B}$ The orbit thus gives the sum of the masses of the two stars. In reality, each star orbits a common center of mass between the two that lies in inverse ratio to the masses. The Earth is 80 times more massive than the Moon, so the Earth has a small orbit about a center of mass that lies 1/80 the distance from Earth to Moon. If we can establish the center of mass, we find the ratio of masses, which with the sum, yields the individual masses.

3. If the stars are too close together, they appear as one in the telescope. But if they are that close, their orbital velocities are high. If the stars are of comparable brightness, we will see two sets of absorption lines. Unless the orbit lies perpendicular to the line of sight, the two sets will alternately shift back and forth via the Doppler effect as one star approaches us and the other recedes. From the amount of shift observed in these "spectroscopic binaries" we can find stellar speeds, which with the period yields orbital circumferences, and therefore semi-major axes, and again the masses from Kepler's Law. Unfortunately, we usually have no way of knowing the orbital tilt, so all we have is the lower limit to the speeds and therefore to the masses. The ratio of speeds still gives the ratio of the masses. Even if one star is too faint to have its spectrum visible, its presence is still noted by the Doppler effect in the spectrum of the brighter star. Such observations can be used to find planets in orbit about stars.
4. Orbital tilt can be found if the orbit lies in or close to the line of sight. Under such conditions, as the stars orbit, they can eclipse each other, one first getting in the way of the other, and then the reverse. From the Earth, we see the star dip in brightness at each eclipse. The most prominent example is Algol (Beta Persei). Every 2.9 days, a luminous hot class B dwarf partially hides behind a larger but dimmer class K giant, and the apparent magnitude drops from second to third and back over only a few hours. In between is a secondary eclipse that takes place when the smaller star cuts in front of the larger. From the graph of brightness against time (the "light curve"), we find the exact orbital tilt, which allows true velocities and actual stellar masses to be found. Moreover, the durations of the eclipses give the dimensions of the stars, which with luminosities (and the radiation laws) give temperatures.
5. Some of these spectroscopic and eclipsing binaries have members so close together that tides can cause the larger star to pass matter to the smaller, denser one, one star growing at the expense of the other (the case for Algol).

C. **The Mass-Luminosity Relation**

1. From all the observations, we find that the main sequence is a MASS sequence that goes from around eight percent of the Sun among the coolest M dwarfs (below which full fusion cannot operate) to more than 100 solar masses among the O stars at the top. The luminosity (L) of a star climbs according to mass (M) raised to the "X" power, where X is between 2 and 4 depending on the exact main sequence location. Double the mass, and the luminosity jumps by roughly a factor of 10. The higher the mass, the greater the internal temperature and pressure, and the greater the rate at which energy is released. Location on the main sequence is controlled strictly by mass.
2. The mass-luminosity relation holds only for the main sequence. Giants and supergiants are too bright for their masses, while white dwarfs are much too faint. White dwarfs typically contain close to a solar mass

stuffed into a volume the size of Earth, which yields an average density of a million grams per cubic centimeter, or a metric ton in a sugar cube. Such huge densities are made possible by the great squeezing room in the atom. Giants, supergiants, and white dwarfs result from stellar death processes, topics for Lectures 8 and 9.

D. **Clusters**

1. The next step up in organization is the cluster. These bear some relation to Trapezium-like multiple stars, in which the members all mill about a common center of mass, each affecting the other. There are so many stars in a typical cluster and so much gravity that the cluster stays nicely together for a long period of time.
2. There are two types of cluster, “open” and “globular.” Open clusters have anywhere from a few to thousands of stars spread out over a volume several light years across, the best known the Hyades and Pleiades of Taurus. There are thousands of such clusters within the Galaxy’s disk, suggesting that a large number of stars are born in such systems.

   Very gradually, they disintegrate, as some stars are sped up by their mates and ejected, the process aided by tides raised by the Galaxy.
3. While not gravitationally bound together, O and B stars are commonly organized into much larger “associations” from which they are escaping. These large structures help make whole constellations such as Orion and Scorpius. They are often centered on open clusters.
4. Globular clusters are much more massive systems, in which anywhere from a few thousand to over a million stars are packed within a volume only a few tens of light years across. Globulars occupy the vast Galactic halo that surrounds the disk. They are characterized by low metal contents, and typically have iron levels only a hundredth of that of the Sun.
5. The lower the mass of the star, the longer it will live. Clusters are commonly born with an intact main sequence, which disappears from the top down. We can tell the age of a cluster from the stars that are still left. Some open clusters are very young, while all globulars very old. Clusters therefore not only tell us much about how stars live and die, but also about the nature of the whole Galaxy, topics for the lectures to follow.

FOR GREATER UNDERSTANDING

Questions

1. How does the organization of stars by constellation relate to the organization by duplicity or by clustering?
2. What is found from binary stars?
3. Go outdoors and locate some naked-eye doubles and clusters.

Suggested Reading

Kaler, J.B. *Stars*. Scientific American Library. New York: Freeman, 1998.

Other Books of Interest

Aitken. *The Binary Stars*. New York: McGraw-Hill, 1935.

Jones, K.G. *Messier's Nebulae and Star Clusters*. 2nd ed. Cambridge: Cambridge University Press, 1991.

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Websites to Visit

1. http://www.astro.uiuc.edu/~kaler/sow/const.html - the constellations
2. http://www.astronomical.org/astbook/binary.html - binary stars
3. http://scienceworld.wolfram.com/astronomy/VisualBinary.html - binary stars
4. http://www.physics.sfasu.edu/astro/binstar.html - eclipsing binaries
5. http://www.seds.org/messier/open.html - open clusters
6. http://www.astro.uiuc.edu/~kaler/sow/cluster.html - naked-eye open clusters
7. http://www.seds.org/messier/glob.html - globular clusters

Lecture 6: Between the Stars

Before beginning this lecture you may want to . . .

Read James Kaler's *Cosmic Clouds*.

Introduction:

The obvious natures of the stars tend to keep our eyes from looking deeper into the vast spaces between them, which contain a good portion of the mass of the Galaxy, just spread so thinly that it is not immediately obvious. Even a casual glance at the Milky Way, however, reveals a thick slab of dust running down the middle, as well as isolated dark splotches that hide the background stars, while the telescope and camera show beautiful lacy interstellar clouds that surround hosts of bright stars. Within the dark stuff stars are born, some of them in turn illuminating their surroundings.

Consider this . . .

1. Is space empty?
2. What are the colorful patches of light that surround some stars?
3. Why are there dark gaps in the Milky Way?

A. **General Remarks**

A significant fraction of the mass of the Galaxy is tied up in interstellar matter, the "interstellar medium" (ISM). Some is illuminated and bright, some is dark to the eye but bright in long-wave infrared radiation, and yet more is visible only in the radio spectrum. It needs to be said at the outset that the ISM consists of BOTH gas (mostly hydrogen, the rest of the elements in near-solar proportions) and "dust," an encompassing term for fine grains of solid particles too small for the human eye to see. Whether it is the gas or the dust or both that manifests itself depends on the local conditions and the observational techniques used. In some situations, it is the gas that is visible, in others the dust—but no matter what it is, both are always present, the dust having about one percent the mass of the gas.

B. **Diffuse Nebulae**

1. Clouds of interstellar matter, whether bright or dark, are called (from Latin) "nebulae." The most readily obvious are the bright "diffuse nebulae" that dot the Milky Way. Of these, the best known is the Orion Nebula, which sits at the center of Orion's three-star "sword" that drops from the equally famed three-star "belt." Even a casual glance with a small telescope or just binoculars reveals swirls of bright gas clouds, which immediately tells us of the existence of matter in the spaces between the stars. Other nebulae of note are the Lagoon and Trifid

Nebulae in Sagittarius, the huge Carina Nebula of the southern hemisphere, and the North America Nebula of Cygnus near Deneb.

2. Diffuse nebulae are lit by bright, hot stars. If a star has a temperature greater than about 25,000 Kelvin (basically, class O), it radiates a significant portion of high-energy ultraviolet light beyond a critical "Lyman Limit" whose energy corresponds to the ionization energy of hydrogen. If a hydrogen atom in the interstellar gas near the star absorbs such a "Lyman photon," the electron will be ripped away, and the atom ionized. When a proton within the ionized gas captures a free electron, the electron gives up the energy gained in the ionization, and radiates (potentially at a variety of wavelengths)—and the nebula visibly glows by fluorescence. Various other excitation mechanisms involve heavier atoms, giving the nebula a rich "emission line" spectrum that is the reverse of the absorption line spectra of stars. Radiation from the star will nearly completely ionize the gas out to a point at which the ultraviolet photons are exhausted, which places a limit on the size of the diffuse nebula. Spectral analysis allows the temperature (about 10,000 K) and the chemical composition (close to solar) to be found. In spite of a nebula's brightness, its density is only a thousand or so atoms per cubic centimeter, thousands of trillions of times less than that of the air in your room. Nebulae are visible because of their great masses.

C. **Dust Clouds**

1. The most obvious nebulae are actually the dark ones that inhabit the Milky Way. They are easily seen with the naked eye as apparent gaps that concentrate down the middle of the stellar pathway. We just do not pay attention to them unless they are pointed out. They cannot be real gaps in the spatial distribution of stars. If they were, stellar motions would fill them in, and they would not exist. Instead, they are cold, unilluminated clouds whose dust simply blocks the light of background stars. In the southern hemisphere, the Incas of Peru and Chile made "dark constellations" out of them. The most famed of the sky is the "Coalsack" next to the Southern Cross. The most obvious in the northern hemisphere is the "Great Rift" that divides the Milky Way in two from Cygnus down to Scorpius and Sagittarius.

2. The dark clouds are dense parts of the interstellar medium that are NOT illuminated by starlight (remember gas and dust are always present together). Illuminate part of a dark cloud with a hot star and you get a diffuse nebula. The dark clouds are best seen in relief against bright nebulae, and are commonly found in tubes called "elephant trunks." But they are also vividly seen against the distant stellar background. Together, all the obvious dark clouds are called "Bok Globules" after the Dutch-American astronomer Bart Bok.

3. The dust particles are typically under a thousandth of a millimeter in diameter. There are fundamentally two different kinds, one whose core is made of silicates (rich in oxygen), the other of carbon. Both carry metal atoms that are absorbed from the gas, and are coated and embedded with ices of various kinds.

4. If a bright star with a temperature under 25,000 Kelvin is near an interstellar cloud, the dust grains will scatter the starlight to produce a "reflection nebula." Molecules in the Earth's atmosphere preferentially scatter the short-wave components of sunlight, which turns the sky blue. Reflection nebulae are blue for the same reason. Diffuse nebulae depend on emission processes from the gas, and are as a result red or green.
5. Interstellar dust, whether distributed in clouds or as a thinner dusty medium between the clouds, absorbs the light of distant stars, making them look dimmer than they would without the dust present. Such interstellar absorption is one of the more severe problems faced by stellar astronomers. If we try to estimate the distance of a star based on its apparent magnitude and the absolute magnitude derived from its spectral class, the dust will make the star appear too far away. All such distances, or all absolute magnitudes calculated from distance and apparent magnitude, must be corrected for this effect. Since the dust preferentially absorbs and scatters blue starlight (to make reflection nebulae), it also makes distant stars seem redder (and of lower temperature) than they would appear without the dust present. The degree of reddening (found by comparing the color of the star with the true color found from its spectrum) leads to an estimation of the absorption along the line of sight and the calculation of true distance or brightness.
6. The dust severely limits our view from Earth. There is so much of it in the Milky Way that we cannot look out of our Galaxy through its disk to see other galaxies. Instead we must look more perpendicular to the disk, where the path-length through the dust is thinner. We cannot even see the center of our Galaxy through the haze. These restrictions can be avoided by observing longer-wave infrared and radio radiation, which penetrate the dust.
7. While dark to the eye, the dust is heated by starlight and glows brightly in the infrared, creating a Galactic "infrared cirrus."

D. **Other Clouds and the General Interstellar Medium**

1. The interstellar medium is a shredded filamentary mix that defies mathematical description. For want of a better word, we call the higher density regions "clouds." Interstellar clouds come in a variety of forms, from diffuse nebulae through warm (100 Kelvin) unilluminated thin clouds, to cold, thick "molecular clouds" near absolute zero, with everything else in between.
2. Pervading the disk of the Galaxy is a very thin layer of neutral atomic hydrogen that makes itself known by the emission of a radio spectrum line with a wavelength of 21 centimeters. This layer, a few hundred light years thick, outlines the Galaxy for us. Where the dusty gases thicken, the dust partially chills the gas by keeping out heating starlight to produce the thin cool clouds. Where the dust thickens greatly, the clouds turn cold, and the hydrogen combines to its molecular form, H2, to create cold "molecular clouds."

3. Pounding through this lumpy, near-incoherent medium are hot gases from exploding stars that raise the ISM temperature to over 100,000 Kelvin. In an example of celestial synergism, the expanding “shock waves”—similar to sonic booms—of the heated gas are collectively one of the driving forces that compresses the dark stuff and helps makes the cooler interstellar clouds.
4. Various disturbances within the Galaxy’s disk create a set of density waves that move outward and push the interstellar medium into a set of graceful spiral arms, where the bulk of it resides. Mapping of the various portions of the ISM allows us to create a picture of what our Galaxy might look like from the outside.

E. **Molecular Clouds**

1. At the heart of the ISM lies the dark molecular clouds, which range from smaller Bok globules to immense structures of over 100,000 solar masses called “giant molecular clouds,” or “GMCs.” The GMCs are the most massive single structures in the Galaxy. Until 1963, the chemistry of interstellar space was unknown except for a couple simple molecules—CH and CN—that superimposed their spectral absorptions onto distant stars. Cold clouds cannot excite atoms or molecules to high energies, and thus their radiations are in the radio. When radio techniques became good enough, we began to discover a plethora of molecules (now over 100) in the ISM, starting with hydroxyl (OH), water, ammonia, and continuing on to formaldehyde, alcohols, acetic acid, urea, and complex structures unknown on Earth. Nearby molecular clouds in Auriga, Taurus, and Scorpius and other constellations make themselves known through the obscuration by dark dust. Among the greatest of GMCs is the Orion Molecular Cloud that is largely invisible to the eye, as it lies in back of the bright stars of the celestial Hunter.
2. Though the gas and dust are very cold, there is plenty of time for chemical reactions to proceed. They are driven by ions in the gas clouds created by energetic “cosmic rays,” high-speed particles driven through the Galaxy by exploding stars, and by processes that take place on the dust grains.

   Where it all ends, no one knows. More complex molecules known as “polycyclic aromatic hydrocarbons” have been found that are made of linked benzene rings. Spectra of interstellar dust suggests sootlike compounds as well.
3. It is within these dark dense clouds that stars are born. New stars can illuminate their surroundings. If the stars are relatively cool, they will produce reflection nebulae from local dust. If they are hot, they will ionize their neighborhood to create diffuse nebulae. Stars buried within the clouds will not be visible optically because of the dust, but will make their presence known through infrared and radio radiation. The Orion Nebula is not a buried nebula, but is a blister on the front side of the Orion Molecular Cloud, illuminated by a quartet of stars (“the Trapezium”),

whose ultraviolet light is eating into the dark stuff behind it. In back of it lie more new, but embedded, stars.

4. Compounds similar to those observed in interstellar space are found in meteorites, pieces of rock from the asteroid belt that hit the Earth.
5. The richness of molecular clouds can take place only in high-density cold environments, where stars are born. The presence of similar molecules in meteorites has led some astronomers to postulate that the seeds of life are created in interstellar space and then deposited on Earth during the time of its formation.

FOR GREATER UNDERSTANDING

Questions

1. What is the relation between interstellar gas and interstellar dust, and of what is the dust composed?
2. List or organize the possible kinds of interstellar clouds.
3. What is the role of molecules in interstellar space?

Suggested Reading

Kaler, J.B. *Cosmic Clouds*. Scientific American Library. New York: Freeman, 1997.

Other Books of Interest

Aller, L.H. *Atoms, Stars, and Nebulae*. Cambridge: Cambridge University Press, 1991.

Websites to Visit

1. http://www.seds.org/billa/twn/ - images of nebulae
2. http://fusedweb.pppl.gov/CPEP/Chart_Pages/5.Plasmas/Nebula.html - nebulae in general
3. http://www-ssg.sr.unh.edu/tof/Outreach/Interstellar/ - interstellar medium
4. http://www.maa.mhn.de/Scholar/interstmat.html - interstellar medium

Lecture 7:
Star Birth

Before beginning this lecture you may want to . . .

Read James Kaler's *Cosmic Clouds*.

Introduction:

Stars have limited fuel supplies, so they cannot live forever. They must therefore have had a beginning, a moment at which they were born. Calculations show that stars substantially more massive than the Sun have lifetimes far less than that of the Galaxy. The hosts of massive stars thus show that stars must be being born even now, in a continuous fashion. The most obvious locations are in the dark, cold clouds where gas and dust can contract to form them, the process leading directly to the birth of planets and of ourselves.

Consider this . . .

1. Where do the stars come from?
2. What can we see of new stars?
3. How common are other planets?

A. **Starbirth**

With some distinctive exceptions, stellar explosions the prime examples, stars do not change much during human lifetimes. We cannot watch a star being born, as the process, though short by stellar standards, is far too long. Instead we compile the evidence for young stars, see where they are to locate the birthplaces, and then connect the pieces together to make a coherent picture. The evidence is everywhere around us, and it all points to the dark molecular clouds as the sites.

B. **Evidence for Youth**

1. O and B stars tend strongly to gang into gravitationally unbound, expanding "OB associations" in which the stars are rapidly moving away from the centers. From their velocities and from their distances from the cores of the associations, the stars must have been recently born. Theory agrees. Massive O and B stars use their internal hydrogen fuel much faster than do lower mass stars like the Sun, and therefore survive on the main sequence for much shorter periods of time, in the extreme case only a couple million years. O stars are also found in proximity to dusty molecular clouds that they often illuminate to produce diffuse nebulae. The conclusion is that the clouds are the stars' birthplaces.
2. Flocking around the dark clouds are hosts of T Tauri variable stars, named after the prototype in Taurus. They are typically mid-temperature F, G, and K stars that are too bright for their classes and that also dis-

play emission lines in addition to the usual absorptions. Erratically variable, they can change their brightnesses by a few magnitudes over intervals of weeks or months. Compared to their visual luminosities, they are also overly bright in both the ultraviolet and the infrared parts of the spectrum. Among the spectrum lines are absorptions of lithium. The element is easily destroyed by nuclear reactions in stars at modest temperatures, so its presence indicates youth. The spectrum of a T Tauri star also reveals that gas is both lost and accreted by the stars. The infrared radiation must come from surrounding dust heated by starlight. There is so much dust that the star should be invisible optically. That the star is seen implies that the dust must be in a disk, which allows us to peek "over the top." Observations with advanced telescopes reveal such disks surrounding many T Tauri stars.

3. The planets of the Solar System orbit the Sun in nearly the same plane, all in the same direction, nearly in the plane of the solar equator, and in the solar rotation direction. The regularity indicates that the planets and Sun were formed at the same time 4.5 billion years ago, and that the planets must have developed from a thick disk of raw material that surrounded the early Sun. The thick disks surrounding T Tauri stars therefore also indicate extreme youth, as they have not yet dissipated or formed planets.
4. Like O and B stars, T Tauri stars group in gravitationally unbound "T associations," their proximity to one another also revealing youth, their proximity to the dark molecular clouds again showing the clouds to be stellar nurseries. The conclusion is that T Tauri stars are evolving in temperature and luminosity toward the HR diagram's main sequence.
5. In the middle of the last century, George Herbig and Guillermo Haro independently discovered small nebulae that had no obvious sources of illumination. For a time it was thought that these "Herbig-Haro (HH) objects" were stars undergoing formation. Astronomers then found that HH objects often came in pairs with a T Tauri star in between them. Moreover, the stars were squirting opposing jets of matter ("bipolar flows") right at them. HH objects are knots of gas illuminated by shock waves caused by the jets ramming into interstellar gas and that are somehow "focused" by the surrounding disks.
6. Radio and infrared observations reveal similar bipolar flows coming from dense condensations of gas within molecular clouds, allowing us to trace the stars back to their origins. The ammonia molecule has a strong propensity to radiate at high densities, allowing us to identify "dense cores" of matter within the dark clouds that are the first glimmerings of new stars. Theory ties all the observations together.

C. **Beginnings**

1. The interstellar medium (ISM) is a messy mix of sheets, clouds, filaments, and condensations of all sorts that is constantly being stirred and compressed by pressure waves within the Galaxy that create its sets of flowing spiral arms. As a result, it is within the spiral arms that we find the ISM, and where we also find star formation. As a result, the

arms are outlined by brilliant O and B stars and their associated nebulae. Add in compression by massive stellar winds and shock waves from exploding stars, and dense cores will automatically be created within the dark clouds. Some of these will be dense enough to begin to contract under the force of their own gravity, and the stage is set to birth a star.

2. Everything rotates, including the huge dense cores. As a core contracts, the conservation of angular momentum makes it spin faster. Like the rotating Earth, it will throw out an equatorial bulge. It ultimately spins so fast that it shatters, preventing the star from forming. Since they obviously DO form, something must first slow down the cloud.
3. The rotating Galaxy contains ionized gas, and therefore generates a magnetic field roughly a millionth the strength of Earth's. The field lines penetrate through the dense cores. Exploding stars produce high-speed atomic nuclei called cosmic rays whose passage produces a string of ions. The ions help generate the parent cloud's chemistry. They also cause the cloud to grasp on to the Galaxy's magnetic field. The ions in turn collide with the dominant neutral atoms and molecules, allowing the magnetic field to act as a brake to the core's rotation, slowing it down. As it becomes denser through contraction, the cloud slips the magnetic bonds, but by then it is rotating slowly enough to allow a growing condensation at the center—a new star—to start to develop. Other processes aid in the slowing, including the formation of the bipolar jets (whose origins are obscure). Fragmentation of a collapsing cloud or capture can create double stars.
4. The contracting cloud will still be rotating. The matter that does not fall into the star will then be spun out to form a dusty disk surrounding the central condensation, from which the new star will for a time continue to accrete matter (that and magnetic activity by rotation producing the observed excess ultraviolet light).
5. As the central condensation contracts, it heats. At a million Kelvin or so, the growing star begins to fuse its natural deuterium into helium. This process slows the contraction and marks a true moment of birth, the array of masses of such new "pre-main sequence" stars forming a "birthline" on the HR diagram above and rather parallel to the main sequence. Convection in the new star keeps the core supplied with fuel. The new star contracts and dims at constant temperature, moving vertically downward on the HR diagram. When deuterium fusion dies down, it swings leftward, and still contracting, hits the point at which the internal temperature is high enough to run the proton-proton chain. The star then rapidly stabilizes, and settles at the left-hand edge of the main sequence, a line (for solar composition) called the "zero-age main sequence," from which it will slowly evolve. That part of the age cycle will be covered in the next lecture.
6. Disturbances in the surrounding disk might cause the disk to form another star, again creating a binary (or multiple) star. Or the dust in the disk could consolidate to make planets.
7. Molecular clouds clearly prefer to make lower mass stars, O stars very rare indeed. The clouds also make brown dwarfs below 0.08 solar

masses below the proton-proton chain temperature cutoff. The lower limit to star formation is unknown. The upper limit is around 100 to 150 solar masses. Not only does the chance of star formation simply vanish above that value, but the pressure of radiation on the outer layers would quickly reduce the mass.

D. **Planets!**

1. If our planetary system formed from a disk, the disks discovered orbiting other stars should produce planetary systems. Unless the disk is disrupted by a close-passing neighbor or radiation from a nearby O star, planets should be a natural by-product of star formation.
2. The standard view is that stars form by condensation from the "top down," while planets form by dust accumulation from the "bottom up," though it is quite possible that the masses of stars and planets can overlap, confusing the difference between the two.
3. Within the disk, orbiting dust grains gently bump and stick, creating larger grains from smaller ones. The process continues until the grains can be visible to the naked eye, from which they grow millimeter to meter to kilometer in size. When big enough, the gravity of the bigger ones helps them swallow little ones until a set of planets orbits the star. Close to the star, it is hot and the new planets cannot grow by accumulating volatile water and hydrogen. Beyond a few astronomical units, it is cold enough to allow such condensation, and the bodies grow fat on hydrogen and wet with ice—making a Jupiter. Beyond a limit, the disk fades away, and the planets can no longer grow large (giving us Uranus and Neptune, while Pluto is stuck as a planetary core). Great collisions melt the bodies, and they differentiate, sending iron to the center, rock to the outside. The result is our—and other—planetary systems. Leftover debris in our system is still seen as asteroids and comets. Faint disks around other mature stars may also represent debris belts, suggesting planet formation has taken place.
4. Shining by reflected light, other planets are too faint to be seen against the glare of their parent stars. However, just as if they were binary companions, planets orbiting other stars will make their central suns orbit a common center of mass, which shifts the stars back and forth along the line of sight. Jupiter-sized bodies in orbit about solar-type stars can therefore be detected by the Doppler effect. Many of the newly found "solar systems" are odd, with a massive "Jupiter" tucked right up against its star. They presumably spiraled in as a result of friction within a dense disk, something that did not happen in our system. We are only beginning to learn of the many faces of other planetary systems.
5. Where there are giant planets, there could be bodies like Earth—unless the inward movement of the giants wiped them out. They are all too faint to be detected.

E. **The Galaxy and the Earth**

Stars are a byproduct of the whole Galaxy, which contains the matter out of which they are made, provides the compression mechanisms that get them started, and produces the magnetic field that allows cosmic rays to slow down their rotations to below a critical limit. As we will see in the next two lectures, the Galaxy also contains the dying stars that make the heavy elements out of which the Earth and other planets are composed.

FOR GREATER UNDERSTANDING

Questions

1. What is the evidence that young stars exist?
2. String together the events that create a new star.
3. What are your thoughts about life elsewhere in space?

Suggested Reading

Kaler, J.B. *Cosmic Clouds*. Scientific American Library. New York: Freeman, 1997.

Other Books of Interest

Cohen, M. *In Darkness Born*. Cambridge: Cambridge University Press, 1988.

Websites to Visit

1. http://www.physics.gmu.edu/classinfo/astr103/CourseNotes/ECText/ch17_txt.htm - stellar structure and star birth
2. http://csep10.phys.utk.edu/guidry/violence/birth.html - star-forming region
3. http://astrosun.tn.cornell.edu/courses/astro201/star_birth.htm - star birth
4. http://www.physics.gmu.edu/classinfo/astr103/CourseNotes/ECText/ch17_txt.htm - stellar structure and star birth
5. http://www.mira.org/museum/birth.htm - star birth

Lecture 8:
Stellar Fate

Before beginning this lecture you may want to . . .

Read James Kaler's *The Little Book of Stars*.

Introduction:

All things ultimately die, perhaps only the Universe itself being immune. Stars are no exception. When their internal hydrogen fuel runs out, they begin their death processes. The final ends may be put off for a time by further nuclear fusion, but the result is inevitable. Along the way some of the most beautiful objects in nature are created, as well as some of the most violent. As stars die, they return much of themselves back into interstellar space, their outflowing matter enriched in star-forming dust and in newly formed chemical elements. The result is that star death enhances star birth and leads ultimately to the formation of planets and the Earth, death begetting life.

Consider this . . .

1. How long do stars live?
2. Where do stars go when they die?
3. What parameters control the lives and deaths of stars?

A. **Ages and Domains**

1. As stars age, they transform themselves from one kind into another, the process called "stellar evolution." A star is caught in a web built by the various forces of nature. Gravity constantly tries to make the star contract to as small a body as possible. Along the way are various pauses that give the star stability. There are also intervals where gravity gets the upper hand, and the star is in a rapid state of change. The main sequence, where the star is supported by hydrogen fusion that keeps gravity at bay, is the first great pause following birth. Other stages explain the whole HR diagram, theory now used to connect all the different kinds of stars that we see.
2. The luminosity of a star (L) is roughly proportional to mass (M) cubed, $L \approx M^3$. The lifetime (t) of a star depends on the amount of fuel (in some proportion to M) divided by the rate of use of the fuel (proportional to L). So $t \approx M/L = M/M^3 = 1/M^2$. Double the mass, and the lifetime quarters. In real stellar life, the effect is even greater. High mass stars live dramatically shorter lives than low mass stars.
3. The proof of this contention is easily seen in star clusters. These groups are born whole from molecular clouds with full main sequences intact. The stars then burn out from the top down, O stars dying first, and so on. It's straightforward to calculate how long it takes for a star at any given spectral class to burn out and leave the main sequence (what

it becomes upon leaving is for now irrelevant). From the brightest and hottest main sequence star left in the cluster, we therefore get the cluster's age. Open clusters range from only a million years (O stars present) to about 10 billion. Globular clusters, burned down to about 0.8 solar mass, are all around 12 billion years old. As the oldest things we know, they provide an age for the Galaxy and the Universe.

4. The main sequence has four great domains. The "lower main sequence" lies between 0.08 and 0.8 solar masses. The Galaxy is not old enough for any star under 0.8 solar masses (roughly class G8) ever to have died. Full hydrogen-burning ends at 0.08 solar masses, which defines the realm of the class L and T brown dwarfs. The "intermediate main sequence" runs from 0.8 to about 10 solar masses. These stars die as white dwarfs, details below. Above 10 solar masses, in the "upper main sequence," which essentially consists of class O, stars explode as "supernovae." Evolution on the lower main sequence is not relevant, as there is no way to check theory. That of the upper main sequence is the subject of the next lecture. Here we look into the fate of the middle.

B. **Main Sequence**

1. A stellar core is a remarkable self-adjusting device. As hydrogen turns to helium, the number of particles diminishes. The pressure of a gas depends on the number of particles, not their kind. But gravity acts to keep the pressure high. As hydrogen burning proceeds, the stellar core must therefore shrink, which raises the temperature and the nuclear reaction rates enough to offset the diminishment of the fuel supply. The result is a stable main sequence, without which life would be impossible.
2. As core temperature goes up, the core's mass grows larger as it slowly eats its way into the surrounding hydrogen envelope. The result is that even while on the main sequence, stars slowly evolve. Though the core's radius shrinks, the release of gravitational energy and the resulting increased temperature cause a higher luminosity, which makes the outer envelope expand and actually cool. Stars therefore move off the zero-age main sequence to the right on the HR diagram, making it into a band. The age of a star can actually be told from its main sequence position (once metal abundance, which shifts the main sequence toward higher temperatures, is accounted for). The Sun was 30 percent fainter when it was born, and when its main sequence life is over, it will be two times brighter. We have one or two billion years left before solar heat will evaporate the oceans and make our planet uninhabitable.

C. **Giants**

1. Rates of stellar change are very slow until nearly all the fuel in the center is gone. When the solar core is all helium, nuclear burning shuts down, and the core must shrink under the force of gravity, again releasing gravitational energy, and driving up the temperature. Hydrogen fusion then spreads out into a shell around the burnt core. The result is dramatic. The star rapidly expands at roughly constant luminosity, cooling to cool G or class K (despite its initial class), and then "turns a cor-

ner," whence it rapidly rises while still cooling some toward class M, becoming a true giant star. The Sun will become over 1000 times more luminous than it is now and will extend past the orbit of Mercury (destroying the little planet) on its way to that of Venus.

2. This growth stage cannot last forever (else the sky would be populated by infinitely bright stars). Nuclear fusion can generate energy by building atoms all the way to iron, whose protons and neutrons are tightly locked together. Similarly, radiative decay can generate energy from heavy elements down to iron. Iron is at the "bottom," the reason there is so much of it. When the core temperature hits 100 million degrees Kelvin, the helium begins to fuse into carbon. The collision of two helium nuclei produces beryllium-8, which is hopelessly unstable. Helium-burning therefore requires a near-simultaneous hit of three helium-4 nuclei, which results in a carbon-12 nucleus. From old-fashioned parlance, a helium nucleus is also called an "alpha particle," helium thereby burning by the "triple-alpha reaction." Another hit by an alpha particle makes oxygen. Hydrogen-burning continues in a shell, but, since the temperature is up, it does so by means of the carbon cycle, which proceeds by using carbon as a nuclear catalyst.
3. Helium burning stabilizes the star, which then shrinks some and dims to about the halfway point of its giant-star rise. Here we find a helium-burning main sequence of stars of different masses. Since some 90 percent of nuclear energy from hydrogen to iron is used in going from hydrogen to helium, the helium-burning state crudely lasts about 10 percent of the main sequence lifetime. Above about 5 solar masses, helium-burning stars can "loop back" all the way to class A and even B before returning to red giant status.
4. When the internal helium is all converted to carbon and oxygen, the core again contracts, and the same thing happens as before, the star swelling to become an even bigger and cooler giant. The dead carbon-oxygen core is now surrounded by a shell of burning helium that in turn is surrounded by one of burning hydrogen, the two turning on and off in sequence (helium-burning beginning violently).
5. In the 19th century, Father Angelo Secchi, who pioneered spectral classification, found a set of very red stars whose spectra contained thick carbon bands. In the Harvard classification called "N," they are all giants and have the same temperatures as class M giants. Warmer versions are called class R, both now just called "carbon stars." In normal stars, oxygen is three times more abundant than carbon. In stars more massive than the Sun, convection can dip way down into the helium-burning zone to bring freshly made carbon to the stellar surface, reversing the carbon-to-oxygen ratio and creating the carbon stars. In between are "S stars," which are identified by bands of zirconium oxide and in which carbon equals oxygen. At the same time, capture of neutrons onto heavy atoms in the helium-burning shell creates heavier atoms, which also get lofted upward. Here is the origin of much of our carbon, nitrogen, zirconium, and various other elements. Lithium, beryllium, and boron get skipped, explaining why they are so rare.

6. Large size lowers the surface gravity and also begins to destabilize the star, causing it to pulsate and to vary greatly in visual brightness. The prototype of such stars is Mira (Omicron Ceti), which varies between magnitudes 3 and 10 and back over a 330-day period. The pulsations of Miras (thousands are known) generate shock waves that drive matter off the stellar surfaces. Some of the lofted gas condenses to dust, which the great luminosity of the Mira drives outward, and the dust drags off the gas in a vast wind that ultimately removes nearly all of the star's outer envelope right down to the old nuclear burning core. Here is the origin of much of the dust of interstellar space, oxygen-rich Miras making silicate dust, carbon stars making carbon dust. Lack of compression from the overlying layers generally prevents the carbon and oxygen from fusing into anything else (though at the top end of the mass range, carbon and oxgyen can fuse to make neon).

D. **The End**

1. Around 1790, William Herschel began to discover small, fuzzy clouds he called "planetary nebulae," the word a synonym for "disklike." At their centers are hot blue stars. Over a thousand are known, their glorious images making some of the finest of celestial sights. As the last of the hydrogen envelope is removed and we see closer to the core, the remaining star heats. It also generates a fast wind that compresses the inner edge of the fleeing mass. When the inner star hits 25,000 Kelvin it generates enough ultraviolet light to ionize the compressed mass, and a planetary nebula is born. As the star heats, the nebula expands and brightens. Eventually nuclear fusion in the core begins to shut down. At a temperature dependent on mass, the star—now nearly the bare core—begins to cool and dim. The nebula finally grows so large it is no longer visible. Carrying by-products of nuclear fusion back into the interstellar gloom, it leaves a cooling white dwarf behind.
2. No longer able to fuse lighter atoms into heavier ones, the white dwarf must be supported by something else. Inside it, the gas is ionized. Electrons, like photons, also have a dual nature, and behave like little waves as much as they do particles. The wave ("quantum") nature prevents those at any given velocity from getting too close together. You can add more, but only at ever-higher speeds. When they have reached this density limit (averaging a metric ton per cubic centimeter), the electrons are said to be "degenerate." Their outward pressure now supports the star. The only fate of white dwarfs is to chill forever, passing from hot and blue to cool and red, the cooling process so slow that no white dwarf has ever disappeared from view. The atom is so vacuuous, however, that even at these densities, there is still a lot of squeezing room—a subject for the next lecture.
3. As the initial mass of a star increases, so does that of the final white dwarf. In the 1930s, Subramanyan Chandrasekhar showed that at 1.4 solar masses, the fastest electrons move with such speeds that Einstein's relativity (which in part deals with the mechanics of bodies moving near the speed of light) must be invoked, and degeneracy

pressure breaks down. White dwarfs cannot be more massive than that limit, which is hit for an initial mass of about 10 solar masses. The O stars, above the initial mass limit, must do something else. Indeed, they explode.

FOR GREATER UNDERSTANDING

Questions

1. What are the pauses in the evolution of a solar mass star?
2. What is the significance of the transitions between the pauses?
3. What is the relation between a main sequence star and a white dwarf?

Suggested Reading

Kaler, J.B. *The Little Book of Stars*. New York: Copernicus Books, 2000.

Other Books of Interest

Kaler, J.B. *Cosmic Clouds*. Scientific American Library. New York: Freeman, 1997.

———. *Extreme Stars*. Cambridge: Cambridge University Press, 2001.

———. *Stars*. Scientific American Library. New York: Freeman, 1998.

Naeye, R. *Through the Eyes of Hubble: The Birth, Life, and Violent Death of Stars*. Wisconsin: Kalmbach, 1997.

Websites to Visit

1. http://www.astro.uiuc.edu/~kaler/sow/star_intro.html - the natures and lives of the stars
2. http://zebu.uoregon.edu/textbook/se.html - stellar evolution
3. http://instruct1.cit.cornell.edu/courses/astro101/java/evolve/evolve.htm - graphical stellar evolution
4. http://observe.arc.nasa.gov/nasa/space/stellardeath/stellardeath_intro.html - stellar evolution

Lecture 9: Catastrophe

Before beginning this lecture you may want to . . .

Read Robert Naeye's *Through the Eyes of Hubble: The Birth, Life, and Violent Death of Stars.*

Introduction:

High mass stars are different, their fates only to explode in mighty bangs that shake the Galaxy and have the power to destroy, but also possess the energy to create. High mass causes the stellar cores to fuse to iron. At the end of the fusion line, the iron cores catastrophically collapse, and the energy released blows the star apart. In the maelstrom, all the chemical elements are created. Double stars add mightily to the entertainment.

Consider this . . .

1. Can stars explode, and will the Sun?
2. If so, what makes them explode?
3. What role do exploding stars play in stellar life and death?

A. **"New Stars"**

1. About once a generation a bright first magnitude visitor arrives on the celestial scene. Seeming new to the sky, such events received the appellation "nova," Latin for "new." Far more are discovered with telescopes. Every couple centuries, however, a vastly brighter "nova" blossoms into the heavens, one that might rival Venus and be visible for a year or two. We now make the distinction between "ordinary novae" (which are surface explosions on white dwarfs) and vastly more powerful ones called "supernovae," which are physically very different and can involve the destruction of entire stars. The most famous supernovae are the Chinese "Guest Star" of 1054, Tycho's Star of 1572, Kepler's Star of 1604, all of which were visible in daylight, and Supernova 1987A, which erupted in the Large Magellanic Cloud (a small, nearby companion galaxy 170,000 light years away) in 1987. The great supernova of 1006, also witnessed by Chinese astronomers, was the brightest celestial event ever recorded, and may have been as luminous as a crescent Moon.
2. There are two basic types of supernova, not surprisingly called Type I and Type II. The first has no hydrogen in its spectrum, while the second one does. Type I is further subdivided into Type Ia, which has a strong silicon absorption, and Ib, which does not. As a clue to how they are made, Type II (and Ib, which for now we lump together) occur exclusively in the disks of galaxies. Type Ia, however, occurs in both the disks and in the haloes of galaxies, as well as in galaxies that have no disks. The disk is where we find the interstellar medium and star formation, and is the exclusive domain of massive stars, which suggests that

Type II events involve high mass stars, whereas Type Ia supernovae do not. Theory fully explains the difference: Type II involves NOT making a white dwarf, while Type Ia speaks to the annihilation of one. Combined, the Galaxy produces about one or two supernovae per century, most hidden behind dust clouds where we cannot see them. Each follows from the discussion of the last lecture.

B. **High-Mass Evolution**

1. Above an initial mass of about 10 times that of the Sun, stars cannot make white dwarfs. This mass closely divides the O stars from the rest of the stellar gang. Only O stars (and the very hot end of class B) have high enough temperatures to illuminate diffuse nebulae. Such stars, readily identifiable by their nebulae, are in line for disaster.
2. At first, high mass stars develop like their lower-mass counterparts, only much more rapidly. They first evolve some on the main sequence, becoming a bit cooler and brighter. When the internal hydrogen fuel runs out, the more common ones of 10 to 30 solar masses quickly swell at nearly constant luminosity to become red supergiants, at which point helium fires up to burn to carbon and oxygen, as before. From about 40 solar masses on up, much rarer stars begin fusing their helium before they can redden, and never become "red supergiants," in part because of fierce winds that significantly reduce their mass. Such great stars heat back to become blue supergiants. Winds and mass loss can strip the envelopes of very massive stars nearly bare of hydrogen and cause them to reveal the by-products of nuclear fusion. At the very top, stars become extremely rare, eruptive "luminous blue variables," of which a Galaxy will contain but a handful. The best example is Eta Carinae, which in the middle of the 19th century erupted an entire solar mass that now surrounds it as a grand dusty nebula.
3. In spite of mass loss, the cores of these massive stars become hot and dense enough to continue nuclear fusion past the helium-burning state. When completed, the carbon-oxygen core contracts and fires up to fuse itself into a mixture of neon, magnesium, and oxygen, the core surrounded by successive shells of the previous nuclear burning phases. When the carbon burning is complete, the neon-magnesium-oxygen core shrinks again, and when hot enough, fuses into silicon and sulfur, which does the same thing, and finally fuses into iron, each stage taking much less time than the one before it. Iron is the end of the line.

C. **Core Collapse Supernovae**

1. Once formed, the iron—an iron white dwarf near the white dwarf limit—cannot fuse to anything and create energy. Briefly supported by electron degeneracy, it begins to contract, and then totally collapses from a ball about the size of Earth to a sphere some 20 km in radius at a good fraction of the speed of light. In the process, the iron, so carefully made by the star, breaks back down into its constituent protons, neutrons, and electrons. Rapidly increasing density causes the protons and electrons to merge into more neutrons with the creation of neutrinos. The collapse is stopped when the density hits that of the nucleus itself, far greater than

that of a white dwarf, 100 million metric tons per cubic centimeter: and a "neutron star" (supported by degenerate neutrons) is born.

2. When the nascent neutron star hits bottom, it violently rebounds. Processes still not clear—the bounce, the pressure of outbound neutrinos, energy generated by convection in the incredibly dense core—send a violent shock wave through the remaining outer stellar envelope, ripping it apart and hurling it outward at a speed of some 10,000 kilometers per second. The extraordinary temperatures, in the hundreds of billions of degrees Kelvin, initiate a huge set of nuclear reactions that chemically propel the expanding mass to move toward nickel and iron. In the process, these reactions (and neutron capture) create nearly all the chemical elements.
3. The energy of the shock wave exploding through the star drives the absolute visual magnitude to -17, approaching a billion Suns, creating a "core-collapse" Type II supernova that can eject more than 10 solar masses into the interstellar medium. Much more energy pours out in neutrinos. After the lustre begins to die away, the fading is controlled by the radioactive decay of a tenth of a solar mass of radioactive nickel, which turns into radioactive cobalt, which finally becomes stable iron. The iron and the other created elements (including those made by the more-slowly evolving parent star) are blasted into the cosmos. The Guest Star of 1054 and Supernova 1987A were Type IIs. Neutrinos from SN 1987A were detected on Earth in just the expected numbers, clearly showing theory to be correct. Eta Carinae is the best current candidate.
4. Type Ib supernovae (which contain no hydrogen absorptions) are caused by the core collapse of massive stars that had previously lost their outer hydrogen envelopes and whose surfaces had been highly enriched in helium, carbon, and nitrogen.

D. **Double Stars**

1. If the members of a binary are sufficiently close, they can interact and exchange mass. If they are not close enough to start with, they can be brought together when one becomes a giant or supergiant and expands past the other to create a common envelope that provides the friction needed to make them spiral into tight proximity.
2. The initially more massive member of a binary will become a white dwarf. If the two are sufficiently close, the white dwarf can raise tides in the ordinary dwarf that are big enough to allow the ordinary dwarf to pass mass to the white dwarf. When the new layer of fresh hydrogen becomes compressed and hot enough, it will explode in a runaway thermonuclear reaction, brightening the white dwarf to a third of a million solar luminosities, and an "ordinary" nova blossoms into the sky. Once the layer is removed, the process starts all over, to repeat anywhere from a few decades to hundreds of thousands of years later, depending on the masses, states of evolution, and the mass transfer rate.
3. If the mass of the white dwarf is sufficiently high, near 1.4 solar masses, the incoming matter may make it overflow the Chandrasekhar (white dwarf) limit, which initiates runaway carbon burning that involves the

whole star. The resulting Type Ia supernova can hit absolute visual magnitude -19, creating the light of several billion suns. It is so bright that it can rival the luminosity of an entire galaxy and be seen billions of light years away. No neutron star is created, as the white dwarf annihilates itself, ejecting all its mass, 1.4 times that of the Sun, into interstellar space. The brilliance is powered by the radioactive decay of a third of a solar mass of radioactive nickel into iron, three times as much as is produced by the Type II events. Tycho's and Kepler's Stars were of this variety. Together, the two kinds of supernova create all the iron in the Universe.

4. The power of supernovae is so great, that any within about 30 light years of Earth would do damage to us.

E. **Supernova Remnants**

1. Type II and Ib core-collapse supernovae leave behind dense neutron stars, or even black holes, that are subjects for the next lecture. Type Ia supernovae leave no condensed cores, as the white dwarfs are destroyed. Both kinds, however, leave expanding shells of illuminated debris that are called "supernova remnants" or "SNRs."
2. The best-known SNR is the Crab Nebula, the remnant of the core-collapse Guest Star of 1054. Some 6500 light years away and a dozen light years across, the Crab is easily visible with a small telescope, its name coming from filaments set within an amorphous blob of gas. It radiates emission lines throughout the spectrum that come from chemically enriched gas set against background "synchrotron" radiation that derives from electrons spiralling around magnetic field lines at nearly the speed of light. Expanding at 1500 kilometers per second, it is powered by an energetic wind from the neutron star at its center.
3. Though there are similar SNRs, the Crab is a bit unusual. Most are not easily seen in the visual spectrum, but in radio and X-ray radiation, their emissions coming largely from shock waves that blast through the surrounding interstellar medium (and in the case of Type II and Ib events through earlier stages of mass loss). The shock continuously sweeps up more and more interstellar stuff until the original exploded stellar material is lost within it. Becoming ever larger, it finally dissipates its energy into interstellar space. In the process, supernovae heat large cavities within the interstellar medium (ISM).
4. Riding the outbound shock like tiny surfers, electrons, protons, and heavier atomic nuclei are accelerated to nearly the speed of light to become "cosmic rays." After spiralling within the magnetic field of the Galaxy, cosmic rays hit the Earth's atmosphere. Smashing atoms into bits, the debris rains to the ground. You sit reading within cosmic ray showers powered by distant exploded stars that reach out to touch you.
5. Multiple core-collapse supernovae that go off within OB associations produce vastly larger combined remnants called "superbubbles" that can break through the ISM of the Galactic disk, making "chimneys" of heated gas that flow out to the Galactic halo.

F. **Synergy**

The most remarkable aspect of stellar evolution is its cooperative nature. Exploding stars create the blast waves that help compress the ISM to produce dense cores, and provide the cosmic rays that help the magnetic field of the Galaxy slow them down to make stars, some of which will in turn explode to create yet newer stellar generations. At the same time, all the stars act together to create the heavy elements that make both the Earth and the people on it, ourselves capable of looking outward to begin to understand it all.

FOR GREATER UNDERSTANDING

Questions

1. How are the different kinds of supernova produced?
2. What are the aftermaths of exploded stars?
3. How do the parts of the Galaxy work together, and how does stellar death create stellar life?

Suggested Reading

Naeye, R. *Through the Eyes of Hubble: The Birth, Life, and Violent Death of Stars*. Wisconsin: Kalmbach, 1997.

Other Books of Interest

Kaler, J.B. *Cosmic Clouds*. Scientific American Library. New York: Freeman, 1997.

———. *Extreme Stars*. Cambridge: Cambridge University Press, 2001.

———. *The Little Book of Stars*. New York: Copernicus Books, 2000.

———. *Stars*. Scientific American Library. New York: Freeman, 1998.

Wheeler, J.C. *Cosmic Catastrophes*. Cambridge: Cambridge University Press, 2000.

Websites to Visit

1. http://www.astro.uiuc.edu/~kaler/sow/star_intro.html - the natures and lives of the stars
2. http://observe.arc.nasa.gov/nasa/space/stellardeath/stellardeath_intro.html - stellar evolution
3. http://www.supernovae.net/isn.htm - supernova enthusiasts network
4. http://www.chapman.edu/oca/benet/mrgalaxy.htm - Mr. Galaxy's Supernovae
5. http://zebu.uoregon.edu/~soper/StarDeath/sn1987a.html - Supernova 1987A

Lecture 10:
Neutron Stars and Black Holes

Before beginning this lecture you may want to . . .

Read James Kaler's *Extreme Stars*.

Introduction:

When the forces of nature are done battling it out, there remain four end products of stellar death: ordinary white dwarfs, strange neutron stars, weirder black holes, and nothing at all. Neutron stars and their manifestations as pulsars abound. Black holes, by their natures, cannot be seen, though indirect evidence leads us to believe that they really exist. The creation of such beasts leads to the most violent events known.

Consider this . . .

1. What are the end products of exploding stars?
2. How do you make a pulsar or a black hole, and why are they different?
3. Can black holes really suck up everything around them?

A. **End Products**

As gravity's great squeeze propels the evolution of the stars to their doom, we find four possible conclusions that depend on stellar mass and duplicity. Intermediate-mass stars between 0.8 and 10 solar masses (unless members of close double stars) die as worn-out carbon-oxygen (or in rare cases, neon-magnesium) cores, as white dwarfs that are destined to cool forever. Above about 10 solar masses, single stars explode as Type II (or Ib) supernovae, most to create neutron stars. Above some critical number (60?, no one knows), the interior mass is so great that a black hole—a star that "disappears" as a result of high gravity—might be made. Double stars add to the mix. In some cases, proximity may be enough that through mass transfer, one star might quietly evaporate the other. Mass loading onto a white dwarf might also exceed the white dwarf limit, causing a catastrophic Type Ia supernova and total stellar destruction. White dwarfs were addressed in Lecture 8. Lecture 9 set the stage for the other end points that will be discussed here.

B. **Neutron Stars**

1. In the 1930s, Walter Baade and Fritz Zwicky suggested that supernovae are caused by stellar collapse into neutron stars. Proof waited three decades, when in 1967, graduate student Jocelyn Bell came into the radio astronomy receiving room to examine the previous night's observations from a new radio telescope designed to detect rapid signal variations. She found the record of a series of pulses with a period of 1.337 . . . seconds. She had discovered the first "pulsar."

2. Several others were quickly found (over a thousand now known). The extreme regularity of the pulses precluded actual “pulsation”—variation in radius—as found in many kinds of variable stars. Only rotation could produce signals this clocklike. White dwarfs could not rotate this fast without disruption. The signal-sources had to be only a few tens of kilometers across: Baade and Zwicky’s tiny neutron stars. The conclusion was sealed when an odd star in the Crab Nebula, one with no absorption lines in its spectrum, was found to pulse at both radio and optical wavelengths with a pulse-period of 0.0331 seconds. Rotating 30 times per second, it is turned “on” for a few thousandths of a second. The Crab pulsar radiates across the spectrum, from gamma ray to radio.
3. Neutron stars, produced by Type II supernovae, typically have the mass of 1.5 Suns packed into a ball only 20 to 30 kilometers across, resulting in densities of 100 million metric tons per cubic centimeter (that of nuclear matter). They are supported by the outward pressure of degenerate neutrons (in the same way that white dwarfs are supported by degenerate electrons). Conservation of angular momentum spins up the initial collapsing iron cores to the observed speeds. The magnetic field of the original star is also collapsed as well, providing new neutron stars with fields of up to a trillion times the strength of Earth’s. A few special neutron stars called “magnetars” seem to generate their own intense magnetic fields of up to 100 times greater. A pulsar’s magnetic field is tilted relative to its rotation axis, causing it to gyrate. If the field is large enough, the neutron star will beam a powerful flow of radiation out along the magnetic axis. If the axis sweeps past Earth, we get a blast of radiation.
4. Neutron stars also produce powerful, magnetically accelerated winds that can energize their surroundings, the Crab pulsar’s wind lighting the Crab Nebula.
5. A rapidly rotating neutron star has enough energy to “pulse” across the spectrum. Radiation removes energy, making the pulsar spin slower. High energy radiation disappears first, then optical, until all that is left is radio. When the pulse period drops to a few seconds, the neutron star gives up radio emission too and disappears from view, except as a hot, still-glowing body.
6. Pulsars have solid surfaces. Crustal cracks (“Starquakes”), or the transfer of rotational energy from a neutron fluid interior, can make a pulsar suddenly spin faster. Starquakes on magnetars (produced by the intense magnetism) are so powerful that even at distances of thousands of light years the resulting radiation can damage Earth-orbiting satellites and ionize the Earth’s upper atmosphere.
7. If a neutron star is in a sufficiently close binary system, hydrogen drawn from its companion will compress and fuse in a bottom layer to helium. When the helium gets hot enough, it violently burns to carbon, resulting in an X-ray nova that can pop off every few hours or days. The infalling mass hits to the side, and can spin a pulsar up to immense speeds, to nearly 1000 rotations per second. The blast from the hot “millisecond pulsar” can also evaporate its mate, the remains consolidating to form “planets” (which have been detected).

8. The detonation of a core-collapse supernova can be off-center, which gives the neutron star a huge kick, sending it speeding along at hundreds of kilometers per second. Any companion it might have might be ejected at high speed in the other direction, creating a "runaway star." (Runaways can also be produced by ejection from multiple star systems.)
9. The mass limit for a white dwarf is 1.4 solar masses, above which it cannot exist. Neutron stars have a similar limit of between 2 and 3 solar masses. Above that they must collapse.

C. **Black Holes**

1. All bodies have an "escape velocity" (v_{esc}) that is needed to place an ejected particle into hyperbolic orbit such that it will never return. The Earth's is 11.2 kilometers (7 miles) per second, the Sun's (at the photosphere) 620 km/s. At a radius of 10 kilometers and with 1.5 solar masses, a neutron star has v_{esc} equal to 200,000 km/s, two-thirds the speed of light. Add some mass and shrink the radius, and we can raise v_{esc} to the speed of light. At that point, light cannot get out of the body, and the "star" disappears from view to become a "black hole."
2. The black hole is defined by a spherical "surface," an "event horizon," inside of which nothing can get out. Overload a neutron star to beyond its degeneracy limit, and it will collapse past the event horizon, and then collapse to a virtual point within it. We can know nothing about what happens inside.
3. The black hole is really a concept from relativity, which views gravity as a distortion of four-dimensional "space-time." Shine a flashlight perpendicular to the Earth. Unlike a thrown ball, the light cannot slow down, but instead loses energy by "reddening" to lower-energy photons. At the event horizon of a black hole, the reddening becomes infinite, and all the light beam's energy is lost. In a loose sense, the black hole might be thought of as a puncture in spacetime.
4. A black hole does not "suck things in" unless something falls toward it. If the Sun were to be one (which it cannot), the planets would keep revolving in orbit just as they do today.
5. How can you see something that radiates no light? If a black hole is close enough to a binary companion, the mate will be tidally distorted and will pass matter toward the black hole. Rather than falling directly into the hole, the transferred mass will first create a disk around it. Intense gravitational contraction will heat the disk, allowing it to radiate X-rays. The best example is Cygnus X-1, in which a 30 solar mass class B supergiant that radiates X-rays—which it is not supposed to do—orbits (as known through the Doppler effect) an invisible 15 or so solar mass body. The only viable speculation is that the companion is a black hole. Various other examples, some of which shoot matter outward in twin beams near the speed of light, are recognized. A black hole might also pass in front of a distant star. Its gravity produces such an intense bending of spacetime that the light from the star is gravitationally "lensed" and becomes brighter.

6. We speculate that a stellar-size black hole occurs as the result of the collapse of the core of a VERY massive star, above 60 solar, which produces “hypernovae.” So much mass falls into the core that it escapes beyond the event horizon. At the same time, the blast produces incredible jets that may explain intense gamma-ray bursts seen coming from distant galaxies. Mergers of binary neutron stars might also produce the bursts.

D. **At the End . . .**

Whatever the scenario, it is clear that stars explode, leaving permanent remnants—or nothing at all—behind. The Galaxy is 13 or so billion years old. The Sun, only five billion years old, had the benefit of the creation of eight billion years of star death and element creation. Elements made in supernovae, together with those made in more ordinary giant stars, give us the gift of Earth—made of the heavy stuff—and of life itself.

FOR GREATER UNDERSTANDING

Questions

1. What are the differences between neutron stars and white dwarfs?
2. What is the life history of a neutron star?
3. How do black holes differ from neutron stars, and how might we detect them?

Suggested Reading

Kaler, J.B. *Extreme Stars*. Cambridge: Cambridge University Press, 2001.

Other Books of Interest

Greenstein, G. *Frozen Star*. New York: New American Library, 1985.

Hawking, S.J. *A Brief History of Time*. New York: Bantam. 1998.

Katz, J.A. *The Biggest Bangs: The Mystery of Gamma Ray Bursts, the Most Violent Explosions in the Universe*. Oxford: Oxford University Press, 2002.

Luminet, Jean-Pierre. *Black Holes*. Cambridge: Cambridge University Press, 1992.

Thorne, K.S., Seitz, F., and Hawking, S. *Black Holes and Time Warps: Einstein's Outrageous Legacy*. New York: Norton, 1995.

Websites to Visit

1. http://www.jb.man.ac.uk/~pulsar/Education/Tutorial/tut/tut.html - pulsars
2. http://www.jb.man.ac.uk/~pulsar/Education/Sounds/sounds.html - pulsars
3. http://www.generationterrorists.com/quotes/abhotswh.html - black holes
4. http://www.generationterrorists.com/quotes/abhotswh.html - text from *A Brief History of Time* (black holes)
5. http://antwrp.gsfc.nasa.gov/htmltest/rjn_bht.html - black holes and neutron stars
6. http://www.eclipse.net/~cmmiller/BH/blkmain.html - black holes and neutron stars
7. http://www.edu-observatory.org/eo/black_holes.html - black holes and neutron stars

Lecture 11: The Galaxy

Before beginning this lecture you may want to …

Read Timothy Ferris's *Coming of Age in the Milky Way.*

Introduction:

Stars cannot be born in isolation, but are the children of parent galaxies, which hold onto them forever. Our Galaxy is a rotating, disk-like structure surrounded by a vast low-density halo, all some 100,000 light years (and more: it just fades away) across that contains not just the stars, but the interstellar matter that produced them, as well as mysterious dark matter whose nature we have yet to track down. At the center is a massive black hole.

Consider this . . .

1. What is the Milky Way?
2. How are stars organized within it?
3. Is there more to the Galaxy than meets the eye?

A. **The Assembly**

1. All stars have parent galaxies to which they belong. And all the stars you see in the nighttime sky are members of our own Galaxy, our home—"us"—identified by the capital "G," no other name needed. Without the telescope, we see very little of it, as all the naked-eye stars are in just our Galaxy's local area. Looking out through the Galaxy, we can see countless other galaxies that contain stars similar to those around us.
2. The essence of our Galaxy is a thin disk of stars and interstellar matter. The density of stars is greatest at the center and drops outward. The Galaxy has no real edge and just fades away, 90 percent of its stars falling within a circle 40,000 light years in radius. Our Sun is located 26,000 light years from the center, about two-thirds of the way from the center to this ill-defined "edge." The disk thickens toward the center into a large but flattened "bulge" with a radius of about 10,000 light years. Surrounding the disk is a vast, sparsely populated "halo" that contains a mere two or three percent of the Galaxy's stars. At the center of the whole assembly lies the Galactic nucleus, believed to be a central massive black hole.
3. In the 1940s, Walter Baade discovered that the disks of galaxies like ours are blue in color, while the bulges and halos are red, revealing two stellar "populations," which he respectively called "Population I" and "Population II."

B. **The Disk**

1. The Sun, a Population I star, lies near the middle of the disk. We see the combined light of the disk stars—all too faint to be seen individually with the naked eye—around us as a broad band of light called the “Milky Way,” which leads to our Galaxy sometimes being called the “Milky Way Galaxy.”
2. The disk contains the Galaxy’s high-mass O and B stars, open clusters, and interstellar matter, the dust component of which can be seen with the naked eye as dark clouds superimposed against the Milky Way’s background. While the disk contains old stars as well, it is also the home of star formation, its brilliant young O and B stars providing its bluish color. An age of 10 billion years is determined from the HR diagrams (which plot stellar luminosities against temperatures) of its oldest open clusters, and from the faintest and coolest white dwarfs (whose cooling times we know from theory). The stars and interstellar matter of the disk have a relatively high metal content, similar to that of the Sun, which increases from the edge into the bulge.
3. As the planets orbit the Sun, the stars of the disk orbit the Galaxy’s center on more or less circular paths. From Doppler shifts of bodies that lie outside the Galaxy’s disk, we find the Sun to orbit at a speed of 220 kilometers per second. Given the orbital radius, we take 225 million years to make a full turn, and have gone around 20 times since birth. The Sun’s path is controlled by the mass of the Galaxy interior to its orbit, which behaves as if it were concentrated to a point at the center, giving us a classic “two-body problem.” Application of Kepler’s Third Law yields the sum of the masses (Sun plus the mass interior to its orbit). A 20 percent correction for the stars and interstellar matter outside the solar orbit gives a Galactic mass of 100 billion Suns. Since the average stellar mass is half a Sun (ignoring brown dwarfs), the Galaxy contains about 200 billion stars.
4. Interstellar dust prevents us from seeing very far into the Galactic disk and prohibits a view of the other side, or even of the center. The disk’s interstellar hydrogen is molecular in the thick dust clouds, atomic in the warmer clouds, and ionized in thin, warm clouds. Atomic hydrogen radiates powerfully at a radio wavelength of 21 centimeters, which punches easily through the interstellar dust. Doppler shifts in the 21-cm emission allow us to determine how different parts of the Galaxy rotate relative to the Sun, and allow the construction of a graph of orbital velocity versus distance from the center. The problem is then turned around to use this “velocity curve” to find the distances of individual clouds (including molecular clouds) from their Doppler shifts. The hydrogen, and also the molecular clouds, are distributed in a set of winding “spiral arms” similar to those seen in other disk-type galaxies. O and B stars follow the spiral arms as well, allowing us to map the local ones. The arms are disturbances that propagate through the disk and are therefore not permanent. The Galaxy rotates as if to wind them up, and new ones form while others dissipate. Once born, stars therefore move in and out of the arms. As density disturbances, the arms are a factor in concentrating the interstellar matter that leads to star formation. As a result, young stars naturally occur within (and outline) them.

C. **The Halo**

1. The Galactic halo is home to the massive globular clusters, as well as to individual stars. Together they constitute two to three percent of the Galaxy's stellar population. Halo stars orbit the Galactic center in long elliptical paths. Since we are moving in a different direction, those that plunge through the disk in our vicinity are identifiable as "high velocity" stars.
2. While we cannot see very far into the disk as a result of its thick interstellar dust, we have a fine view of the halo and its contents. Distances to globular clusters are easy to find from their HR diagrams by comparing the apparent magnitudes of their stars with the absolute magnitudes they should have based on their diagram locations. From the spatial distribution of the globular clusters and the assumption that it is symmetrical about the Galactic center, we can find the center's distance (which agrees with other methods).
3. There are no young stars in the halo; they are all old and of similar ages. The most massive stars left on the main sequence (as found from globular cluster HR diagrams) give ages of 12 to 13 billion years. Since these are the oldest objects known, that figure is taken as the age of the Galaxy. (It is remarkably similar to that found for the age of the Universe from its expansion, as noted in Lecture 13).
4. While the globular clusters and free halo stars show a spread in metal content, they are all metal-deficient compared with the metal content of the disk. Globular cluster metallicities range from a hundredth that of the Sun to a tenth. Some freely orbiting stars have much lower metal contents that range to a hundred-thousandth solar. The relation between age and metal content is consistent with metals being created in stars and with their winds and explosions continually enriching the interstellar medium (from which stars are born) in heavy elements.

D. **The Bulge and Nucleus**

1. The Bulge, where the halo and disk merge, contains about 10 percent of the Galaxy's stars. Metal contents are a mix of high and low. Except for the inner disk that slices through it, its stars are all old, the red giants giving it its reddish color. The star density (stars per unit volume) gets amazingly large. Near the central disk are huge numbers of young stars and massive clusters.
2. In the early days of radio astronomy, a bright source of radio radiation from the thickest part of the Milky Way was dubbed "Sagittarius A." Better observations reveal a tiny core called "Sagittarius A*," which is only an Astronomical Unit across and is now considered to be the actual core of our Galaxy. Application of Kepler's Third Law to the orbital motions of stars around it give a mass of over two million solar masses. The most likely conclusion of all this mass tucked into such a small volume, combined with intense radio emission, is that the nucleus of the Galaxy is a "supermassive black hole" whose radius would be but a few hundredths of an AU. The emission comes from a hot disk encircling the black hole

made of interstellar gas and torn stars that are all falling into it. Support for such a monstrous black hole comes from observation of the nuclei of other galaxies, some of which are far more massive than Sagittarius A* (as considered in Lecture 12).

E. **Dark Matter**

The disk continues faintly to distances from the center of more than 75,000 light years. If the vast bulk of the matter of the Galaxy were inside the orbit of the Sun, as seems apparent from stars and the interstellar medium, then the orbital speeds of stars outside the solar circle should decrease in accord with Kepler's Laws, just as the speeds of planets dramatically decrease with solar distance. They do not, but instead just keep moving at near the solar speed. For that to happen, as you increase the radius of a star's orbit, you must proportionately increase the mass enclosed within it. But we do not see that mass. It is not there in small amount, but has many times the mass tied up in "bright matter," stars and the standard ISM. Some of it is likely to be in the form of difficult-to-detect ordinary matter, which leaves most in a mysterious and unknown form called "dark matter" (the subject to be examined further in the lectures to follow). Dark matter is detected only through its gravity, and constitutes a large fraction of the mass of other galaxies and their clusters—and of the Universe at large. Though many are the candidates, we simply do not know what it is. In our Galaxy, the dark matter is distributed in a huge "dark matter halo" into which our visible Galaxy is set.

F. **Evolution**

1. The original idea of how the Galaxy formed is a grander version of star formation. The Big Bang (Lecture 14) produced hydrogen and helium gas in an ever-expanding Universe. Much of the gas chaotically formed condensations that could become dense enough to collapse under their own gravity. The first stars formed during the contraction. Their explosions and winds contaminated the gas with the first heavy elements, which later found their way into condensing globular clusters and other low-metal Population II stars. Since the Galaxy was then contracting, these stars and their clusters were launched into highly elliptical orbits. The rotating collapsing mass of gas contracted to form a spinning disk, whose developing stars were further enriched by the evolution of the stars of Population II, which led to the higher metal stars we see today as Population I.
2. The correlations between age and metal content are not all that good, however. Looking back in time to distant galaxies shows that they were not as well formed as they are today. Moreover, we see galaxies colliding. An alternative is that our Galaxy was built from smaller systems, each of which was in its own state of evolution. The truth probably lies in a combination of the ideas.
3. Whatever the case, the first stars should have had zero metals. These "Population III" stars have never been found. However, ultra-low-metal stars (whose metal contents are 1/1000 lower than the lowest-metal clusters) have the chemical signatures expected from core-collapse supernovae, suggesting that Population III consisted of only a few high-mass stars, just enough to get Galactic evolution underway. We will pursue this subject to its conclusion in the next three lectures.

FOR GREATER UNDERSTANDING

Questions

1. Outline the different parts of the Galaxy. How are they seen by us?
2. What evidence is there for dark matter and for a supermassive black hole in the Galaxy's center?
3. How might the Galaxy have come to be, and what is the evidence?

Suggested Reading

Ferris, Timothy. *Coming of Age in the Milky Way*. New York: Anchor, 1989.

Other Books of Interest

Bok, B. and Bok, P. *The Milky Way*. 5th ed. Cambridge, MA: Harvard University Press, 1981.

Ferris, Timothy. *Galaxies*. New York: Random House, 1988.

Websites to Visit

1. http://www.seds.org/messier/more/mw.html - the Milky Way Galaxy
2. http://adc.gsfc.nasa.gov/mw/milkyway.html - the multi-wavelength Milky Way
3. http://www.damtp.cam.ac.uk/user/gr/public/gal_milky.html - our Galaxy
4. http://casswww.ucsd.edu/public/tutorial/MW.html - structure of the Milky Way

Lecture 12: Galaxies

Before beginning this lecture you may want to …

Read Timothy Ferris's *Galaxies.*

Introduction:

A century ago, we did not even know there were such things as other galaxies, most astronomers thinking ours was the only one. They are everywhere, in all imaginable forms and sizes, from tiny scraps through elegant spirals to giant ellipticals, the larger ones containing magnificent central black holes. Most galaxies belong to great clusters that stretch off into the distance as far as we can see, their number entirely uncountable even by generations of astronomers. Nearly everywhere we see more evidence of the mysterious dark matter.

Consider this . . .

1. Are we alone, or are there other galaxies?
2. Are all galaxies the same? If not, how do they differ from one another?
3. How are other galaxies affected by dark matter?

A. **Background**

1. Although the concept of "island universes," other galaxies, goes back to the 18th century, the debate between ours being the only galaxy and the concept of multiple galaxies raged until Edwin Hubble proved in the 1920s that the Andromeda Galaxy (M 31) was an external system much like our own. He was first to resolve another galaxy into stars, and if they were anything like those in our own Galaxy, M 31 had to be far away, and outside ours. From that point on, "extragalactic astronomers" discovered and catalogued ever more of them, found a large fraction to be in clusters, and in our own times expanded our view out to billions of light years. The number of galaxies in the visible Universe vastly outnumbers the stars within our own Galaxy. The "Hubble Ultra Deep Field" (described more in Lecture 14), which is but a tenth the angular diameter of the Moon across, contains 10,000 of them, each at least something like our own.
2. Four galaxies are close enough to be seen with the naked eye. In the northern hemisphere lies easily visible fourth magnitude M 31. At a distance of 2.2 million light years, it is the farthest thing most people can see with the naked eye, appearing as an elongated fuzzy patch in central Andromeda. M 31 is much like our Galaxy, except more massive. Excellent eyes in a dark site might also see the smaller, slightly more distant (2.3 million light years) Triangulum Spiral, M 33, which contains about a tenth the mass of our Galaxy. Deep in the

southern hemisphere lie the Large and Small Clouds of Magellan, named in honor of the explorer. They are small satellites to our Galaxy. With about one percent the mass of our system, the Large Magellanic Cloud (LMC) is 170,000 light years away, the Small Cloud (SMC) a bit smaller and farther. Easy to resolve into stars, the Clouds are natural laboratories for the study of relative stellar properties. M 31 has similar (though differently structured) companions that can be seen through a small telescope.

B. **Structure and Classification**

1. As for stars, the first step is to see what kinds of galaxies there are and to classify the data. The basic scheme was invented by Edwin Hubble. Galaxies fall into two very broad categories, “spirals” and “ellipticals.” The remaining scraps are called “dwarfs” and “irregulars.”
2. Spirals, like our Galaxy, are constructed of thin disks with central bulges and encompassing halos. They are classed according to the winding of the arms, tight arms called “Sa,” loose and open ones “Sc.” Ours is in the middle, roughly Sb. A subset of spirals has a “bar” running through the centers from which the arms emerge. Like the “normal spiral,” these barred, or “SB,” galaxies run in arm-openness from SBa to SBc. The disks and spiral arms of both kinds contain interstellar matter, are the sites of star formation, and are therefore blue in color. The more open the arms, the more active the star formation, and the smaller the central bulge.
3. Elliptical galaxies have no disks, but are all “halo,” though the analogy is loose, as they are tightly packed with stars and are of more normal metal content. Ellipticals are classed from E0 for those appearing as circles (which might be “footballs” pointing at us) to E7 for quite elongated ones. They are nearly devoid of interstellar matter, exhibit no star formation, and are reddish in color as a result of their evolving lower-mass red giants, rather like the Galactic bulge.

C. **Distances**

1. Classification means little without physical data, and number one is distance. In principle it is easy to get a galaxy’s distance. You need only recognize a star or other body—a “standard candle”—whose absolute magnitude you know from studies of our own Galaxy, measure the apparent magnitude, account for dimming by dust, and calculate how far it is.
2. Among the best standard candles are “Cepheid variable stars.” Mid-temperature (classes F and G) supergiants are inherently unstable, and pulsate like Mira variables, but with lower ranges of a magnitude or two and with shorter periods, a couple days to weeks. Around 1912, Henrietta Leavitt found that the longer the pulsation period, the more luminous the star, that is, the period gives the absolute magnitude, which when combined with apparent magnitude yields distance. Edwin Hubble used such Cepheids in his determination of M 31’s distance. One of the “key projects” of the Hubble Space Telescope was to measure Cepheid distances, and thereby those of their host galaxies, to some 200 million light years away.

3. Many of these galaxies whose distances are known from Cepheids (and from similar standard candles such as ultrabright stars, novae, and planetary nebulae) have popped Type Ia (white dwarf) supernovae, from which we have derived their peak (and very similar) absolute magnitudes. These supernovae are so bright and uniform that we can use them to measure the distances of galaxies billions of light years off.

D. **Properties**

1. Once distances are known, we find dimensions and masses. The mass of a disk or spiral galaxy is determined by observing the velocities of orbiting stars at known distances from the galaxy's center, which gives the orbital periods. Application of Kepler's Third Law then allows computation of the mass interior to the orbits in the same way that we find the mass of our own Galaxy. Masses of ellipticals are found through the stellar velocities as well, as these respond to galactic mass.
2. Spirals are typically large and comparable to our own Galaxy, M 31, and M 33. Ellipticals, on the other hand, span a huge range of masses, from the smallish ones that accompany M 31 to monster "giant ellipticals" that can have 100 times the mass of ours. At the bottom are the small irregulars like the Magellanic Clouds and various scrappy dwarfs in which star formation can still go on at a high clip.
3. As in our Galaxy, the speeds of rotating spirals do not drop off with distance, showing much the same amounts of dark matter, which is also distributed in "dark matter halos." Elliptical galaxies contain similar dark matter as well.

E. **Clusters of Galaxies**

1. Galaxies, especially ellipticals, have a strong propensity to form clusters. We live in a small cluster of three or so dozen galaxies called simply the "Local Group." It is anchored by two large spirals, ourselves and M 31, into which is mixed M 33, the Magellanic Clouds, and a host of dwarfs.
2. Nearby clusters are named after their constellation of residence, distant ones by catalogue number. The nearest large system is the Virgo Cluster, which occupies much of that constellation, contains some 1000 galaxies, and is about 50 million light years away. Our Local Group rather lies on the fringe of it. In nearly the same direction but 300 million light years off is the rich Coma Berenices cluster. Galaxy clusters scatter off into the distance as far as we can see, millions of them known.
3. The individual galaxies of a cluster orbit its common center of mass. Orbital speeds will depend on the cluster's total mass. Though we cannot get actual orbital data, we can measure the relative line-of-sight velocities within the cluster, from which we can statistically infer orbital velocities. Such velocities are much higher than expected on the basis of the amount of optically visible (bright) matter, showing that the whole cluster is filled with dark matter. Some of it is hot intergalactic matter that radiates X-rays. But some six times the bright matter mass is tied up in true mysterious form. Dark matter seems everywhere, and no one knows what it is, though exotic atomic particles are suspected.

4. Within the dense confines of a galaxy cluster, even in a poor one like ours, the individuals can collide. Since the stars of a galaxy are far apart, they do not hit; rather, the galaxies simply pass through each other. However tidal effects can severely distort the galaxies and dissipate energy, while shock waves that involve the collision of the interstellar matter within the systems can enhance star formation. One result is the stripping of interstellar gas, which falls toward the core of the cluster to feed a giant elliptical. Another is merger of the two into a larger system, with tidal scraps tossed around. Larger structures, superclusters and more, exist and will be a subject for the next lecture. Such collisions can enhance spiral arm formation, and can apparently also make an elliptical out of two spirals. They also show that galaxies grow by mergers, supporting the merger theory of the formation of our own system. The kind of galaxy, whether elliptical or spiral or whatever, may depend on initial rotational characteristics and merger history.

F. **Galactic Nuclei and Active Galaxies**

1. At the centers of larger galaxies are tiny bright nuclei that seem similar in structure to the nucleus of our own Galaxy. We can measure the masses of the nuclei through the orbits of surrounding stars and interstellar matter. We find intense concentrations of matter that suggest central black holes, which can range into the low billions of solar masses, far more than we find in our own system.
2. From the nuclei of a small fraction of galaxies pour twin opposing jets that can extend for millions of light years and far beyond the confines of the parent systems. Knots in the jets of these “active galaxies” can move near the speed of light. Radio and other observations reveal radiation produced by electrons spiralling in magnetic fields. Such activity is seen in both spiral and elliptical galaxies. It seems to be caused by matter falling into the central black holes and heating to become visible before it disappears, while some of it is whirled outward in twin beams by magnetic fields.
3. At great distances, in the billions of light years, we see brilliant starlike optical and radio sources that in the 1960s were dubbed “quasi-stellar radio sources” or “quasars” (though now we know most are radio “quiet”). They are active nuclei of galaxies so far away (and so underdeveloped) that the galactic forms are difficult to see. As we look at such distant bodies, we look back billions of years into the past. The brilliance of quasars show that galaxies could be much more active in the past than they are today. The subject leads directly to the next lecture, wherein we begin to examine the Universe at large.

FOR GREATER UNDERSTANDING

Questions

1. What forms can galaxies take?
2. How do galaxies group together?
3. What is the sum of evidence for dark matter?

Suggested Reading

Ferris, Timothy. *Galaxies*. New York: Random House, 1988.

Other Books of Interest

Sandage, A. *The Hubble Atlas of Galaxies*. Washington, D.C.: Carnegie Institution of Washington, 1961.

Tayler, R.J. *Galaxies: Structure and Evolution*. Cambridge: Cambridge University Press, 1978, 1993.

Websites to Visit

1. http://www.seds.org/messier/galaxy.html - galaxies
2. http://www.damtp.cam.ac.uk/user/gr/public/gal_home.html - galaxies and the Universe
3. http://www.smv.org/hastings/galaxy.htm - interactive galaxy lesson
4. http://www.astro.princeton.edu/~frei/galaxy_catalog.html - galaxy catalogue
5. http://www.seds.org/messier/spir.html - spiral galaxies

Lecture 13:
The Expanding Universe

Before beginning this lecture you may want to . . .

Read E.R. Harrison's *Cosmology*.

Introduction:

The most outstanding characteristic of the Universe is not its galaxies, nor its number of galaxies, nor its dark matter, but its expansion. Originally a theoretical concept, it proved to be real. It is not an expansion of galaxies through the Universe, but an expansion of the space of the Universe itself in which the galaxies go along for the ride. The discovery led to the current theory of the formation and evolution of the Universe, the Big Bang.

Consider this . . .

1. If everything has gravity, why do the galaxies not fall together all in a lump?
2. What exactly is the expanding universe? What is expanding?
3. How old is the Universe?

A. **Einstein**

With this lecture we embark upon the ship of "cosmology," the study of the cosmos, of the Universe at large. Shortly after the creation of the theory of relativity, Einstein and others began to use it to find the nature of the spacetime of the Universe. (Spacetime is the four-dimensional construct that melds space and time; gravity is considered to be the result of the curvature of spacetime caused by the presence of mass.) Einstein noted that gravity would bring everything, all the stars (and galaxies, though there was no agreement on their existence) together, that is, it would collapse space. To create a "static universe," that is, to balance gravity, Einstein postulated an outward, expansive "cosmological force." Others, however, found solutions to Einstein's equations that required the Universe not to be static, but to be already in a state of expansion, which by its very nature would prevent contraction. Einstein later referred to the cosmological force as his "greatest blunder." His cosmological force may well be present, with effects that no one envisaged.

B. **Observed Expansion**

1. By 1912, Vesto Slipher had observed the spectra of over three dozen of the then-mysterious "spiral nebulae," and found that with the exception of M 31, one of its companions (M 32), and M 33, they were all moving away from us at speeds of up to 1000 kilometers per second. This discovery strongly suggested that the nebulae were actual external galaxies, as their very motion would have to take them out of our Galaxy's confines. By around 1930, Hubble had derived the distances to some

two dozen galaxies, most by comparison with the galaxies that were resolvable and amenable to direct measure. A graph of velocity against distance revealed a clear linear relation, that the farther away the galaxy, the faster it was receding from us. Hubble had discovered the real expanding Universe. The only galaxies coming toward us are a few in our local group, in which the galaxies are orbiting a common center of mass and are unaffected by the general expansion.

2. The recession velocity of a galaxy is determined by what at first appears to be a Doppler shift in the galaxy's spectrum. Since the galaxy is moving away, its spectral absorptions are shifted to longer wavelengths, that is "to the red." Astronomers determine the outbound speed through this "redshift" = "z," which is the fractional displacement in wavelength z = (observed wavelength - true wavelength)/true wavelength. The Doppler formula is velocity v = cz, where "c" is the speed of light.
3. By the mid-1930s, Hubble and his assistant Milton Humason had reached z = 0.132, implying through the Doppler formula a recession speed over 40,000 kilometers per second. Continued and much deeper observation showed the relation between distance and redshift (hence velocity), the "Hubble relation," to be straight as an arrow, wherein the redshift (and thus velocity) is directly proportional to distance.
4. The Hubble relation applies only to the large scale, really to isolated galaxies and to clusters of galaxies. The galaxies within a cluster are bound by gravity, which prevails, so that the cluster is not getting larger with time. Neither is our Galaxy nor the Solar System.
5. The Hubble relation is independent of direction, implying that we are at the center of some vast expansion. A little thought, however, reveals this centric view to be an illusion. Since speed is proportional to distance, all galaxies (rather their clusters) are moving away from all other galaxies. No matter in which one you lived, you would see the same thing and appear to be at the center of the expansion.
6. The rate of the expansion is expressed through the "Hubble constant," H_o, in kilometers per second per million light years. Astronomers struggled through most of the 20th century to find it, some discussions becoming quite heated. Its determination is confused by difficulties in determining accurate distances (including the proper calibration of the Cepheid variable period-luminosity relation), and by local, gravitationally driven motions that deviate a galaxy from the smooth "Hubble flow." As best we can now determine, H_o stands at 22 km/s per million light years. That is, a galaxy 10 million light years away is receding at 220 km/s, one at a billion light years at 22,000 km/s.

C. **Meaning of the Expansion**

1. The Doppler formula expresses velocity in direct proportion to redshift. Modern observations show redshifts beyond 1, which implies speeds much faster than light. The record is greater than 6! The redshift is in fact NOT a Doppler shift, but is instead caused by the expansion of space itself. Imagine galaxies sprinkled out onto a sheet of rubber graph paper that represents space. If you pull smoothly on all sides of

the sheet, expanding it in all directions, the galaxies maintain their relative positions to the graph's grid, but get farther apart with speeds in proportion to their separations. The galaxies are merely travellers in space's persistent expansion.

2. The Hubble (or "cosmological") redshift is caused by this expansion of space. As galaxies are caught in the web of space, so are photons. A photon is released from a distant galaxy to us. As it flies toward us, space expands and the photon stretches along with it. By the time it arrives at us, it is longer, hence redder. The more distant the galaxy, the longer the flight time, and the greater the stretching and the redshift. At low velocities, the formula for converting redshift into velocity is very close to the Doppler formula (allowing it to be used, and perpetuating the myth that the Hubble redshift is Doppler). But at high velocities, it diverges from Doppler to a degree that depends on the "shape" of spacetime (that story told in the last lecture), such that there is no single equation that can be used.
3. Galaxies can have their own motions against the grid caused by gravity that produce REAL Doppler shifts superimposed onto the redshifts produced by the expansion of space. These can make it difficult to find the Hubble expansion, as they must first be removed. The use of Type Ia (white dwarf) supernovae to get distances voids that issue as the cosmological redshift is so great that we do not have to worry about the real, but small, Doppler shifts.

D. **Mapping the Universe**

1. If redshift is proportional to distance, and we know the correct correlation (hence Hubble constant), we can turn the problem around and use redshifts to calculate distances. Even if the Hubble constant is NOT accurately known (which it now is), we can still obtain relative distances. By measuring the redshifts of thousands—even millions—of galaxies we can find their distribution in space. The problem of real Doppler shifts remains, however, and they can skew the conclusions. The distances of quasars, now believed to be caused by supermassive black holes in early galaxies, are found by this means.
2. The results clearly show anything but a uniform distribution. Instead, we see a frothy, spongy structure, with clusters of galaxies set into "walls" and long strings that enclose huge voids that theories for the origin of the Universe must explain. We do not find "smoothness" until we average out regions of half a billion or so light years across.

E. **Age of the Universe**

1. While there have historically been other theories regarding the state of the Universe, the uniform expansion in all directions leads to the conclusion that all of its mass and energy were at one time condensed into a hot, dense state from which the expansion began: a "Big Bang" (which is properly the subject of the last lecture). The concept implies that the Universe, at least as we see it today, had a beginning and must also have an "age."

2. The Hubble constant, H_o, describes the rate at which the Universe expands in km/s per million light years, and is derived by dividing the velocity by the distance. However, if you know how far away a galaxy is, and divide by the velocity, you get the time it took for the galaxy (rather the mass and energy that made it) to get from us to its present distance. Since velocities and distances are directly proportional to each other (at least before the velocities get too large), we get the same answer no matter what galaxy we use. That is, the age "t_o" is just the inverse of the Hubble constant, $1/H_o$.
3. A Hubble constant of 22 km/s per million light years gives an "age" t_o = 13.8 billion years. Since gravity might act to slow down the expansion, and since spacetime might be curved as a result of the gravity in the Universe (again, a subject for the last lecture), this number might not be the actual age, but at least it is an indicator of real age. Most remarkably, the age of the Universe derived from its oldest members, the globular clusters (and from a completely different point of view, that of stellar evolution), is—at 12 to 13 billion years—quite similar, strongly suggesting that we are doing something right.

F. **The Distant View**

1. Cosmologists long simply assumed that the expansion rate of the Universe should slow down with time as a result of the drag produced by gravity. The rate of slowing would depend on the Universe's average density. If so, the Hubble relation (redshift vs. distance) should at some great distance seem to bend from a straight line.
2. The discovery of the uniformity of Type Ia (white dwarf) supernovae gave the opportunity to test this hypothesis, since these exploders can be seen so very far away.
3. Remarkably, instead of a slowing of the expansion rate, astronomers found that the expansion rate is increasing! That is, the Universe is "getting larger" at an ever increasing rate. No one knows why. But Einstein's "greatest blunder," the cosmological force—or some sort of mysterious "dark energy" that it takes to cause the acceleration—is once again invoked. The master may have been right after all.
4. Most of the data are now in. Only one spectacular observation is yet to go, one that fully supports the above conclusions, and that with other data tells us that the Big Bang really happened. Turn then to the last lecture, where the entire Universe and its structure comes under scrutiny.

FOR GREATER UNDERSTANDING

Questions

1. What is the Hubble constant, and how does it relate to the age of the Universe?
2. What evidence leads to the concept of the Big Bang?
3. What observations led to a concept of an accelerating Universe, and how does it relate to Einstein's predictions?

Suggested Reading

Harrison, E.R. *Cosmology*. Cambridge: Cambridge University Press, 1981.

Websites to Visit

1. http://astsun.astro.virginia.edu/~jh8h/Foundations/chapter10.html - expanding Universe
2. http://www.ncsu.edu/felder-public/kenny/papers/cosmo.html - expanding Universe
3. http://hyperphysics.phy-astr.gsu.edu/hbase/astro/hubble.html - expanding Universe
4. http://map.gsfc.nasa.gov/m_uni/uni_101expand.html - expanding Universe

Lecture 14:
Cosmic Origins in the Big Bang

Before beginning this lecture you may want to . . .

Read Leon Lederman and David Schramm's *From Quarks to Cosmos: Tools of Discovery.*

Introduction:

What we know as our Universe seems to have begun as a sudden expansion from a hot dense state. We live in the result 13 to 14 billion years after the initial event. The energy inherent in the Big Bang converted to material particles, to matter, which condensed further into stars and galaxies. The Big Bang is not speculation, but is a complex and well considered theory that is supported by a large amount of observational data. The Universe is made only partly of what we call normal matter. Most is in the form of dark matter and even more mysterious dark energy. We seem far from solving all the riddles. What more riddles remain to be discovered?

Consider this . . .

1. What possible theories explain the expanding Universe?
2. Where did it come from?
3. And where is it going?

A. **Cosmological Principles**

1. We begin by looking at our Universe through a set of principles that help organize our options. For most of human existence, we have thought ourselves at the center of everything, of space and whatever our current concept of the Universe happened to be. One of the powerful roles of science has been to displace that view.
2. Copernicus began the journey by placing the Sun at the center of the known Universe and recasting the Earth as one of the many planets. The "Copernican Principle" states that "the Earth is not special."
3. We then found that the Sun was not centered in the Galaxy, nor the Galaxy in the Universe. While individual astronomical objects and systems do have centers, the Universe at large has none. The "Cosmological Principle" states that "No place is special," that is, from any given place you would see pretty much the same thing.
4. What about time? Extend the principle farther to the "Perfect Cosmological Principle," which holds that "There is no special place or time." Neither from where nor when you looked at the Universe would make any difference.

B. **Competing Theories**

1. The Cosmological Principle allows a time-evolving Universe, while the perfect version does not. The latter was the foundation of the "Steady State Theory," championed by Fred Hoyle and others. To be constant in space and time as the Universe expands, new matter must continuously be created such that we always see the same thing. The Steady State Universe has neither beginning nor end.
2. The alternative, evolving Universe is described by the "Big Bang" theory, which was created by the early cosmologists and held aloft in later times by George Gamow. It holds that all the stuff of the Universe was at some moment (the "age of the Universe ago") closer together and in a "hot, dense state." By mathematically reversing the expansion, we can trace the Universe's conditions back to the time when it was 10^{-43} (1/[1 with 43 zeros]) seconds old and the temperature stood at 10^{31} (1 with 31 zeros) Kelvin. Before that, the conditions were so extreme that the known laws of nature break down. As the Universe expanded, the temperature cooled, and the photons radiated by it "cooled" too, that is, the expansion of the Universe stretched them out, reddening them, just as it does with the light from distant galaxies. In the 1940s, Gamow and his group predicted that the Big Bang "fireball" should have chilled to only a few degrees Kelvin.
3. In 1965, Arno Penzias and Robert Wilson discovered that we live in a bath of radio radiation coming at us from all directions. Measures at different wavelengths told of radiation from a blackbody at 3 degrees K (later refined to 2.728... Kelvin), close to the prediction. They had discovered the cooled Big Bang fireball, effectively putting an end to the Steady State theory. We live in an evolving Universe that had a beginning.

C. **Structure**

1. If the Universe had a beginning, does it have an end? There are three traditional scenarios. The mathematics of plane geometry were derived by the ancient Greek Euclid from a set of "obvious" principles. His "fifth postulate" states that given a line and an external point, one and only one line can be drawn through the point parallel to the original line. If so, the angles of a triangle add to 180 degrees. Spacetime is then considered to be "flat," or "Euclidean."
2. Perhaps there are no such things as parallel lines, that lines that appear parallel to us meet somewhere in the vast distance. If so, space is curved back on itself as a multidimensional "sphere," and the angles of a triangle sum to more than 180 degrees. Perhaps too that MORE than one parallel line can be drawn through Euclid's point. If so, space is curved outward and open, and the triangle-angles sum to less than 180 degrees.
3. If the Universe is spherically curved, there is nothing outside the "sphere." Moving in a straight line, we would return to our starting point. If the Universe is flat or open, it is infinite. In no case can there be center or edge.

4. The curvature depends on the gravity of the Universe, hence on the amount of matter per unit volume, the smoothed-out density. Low density means that the Universe is curved outward and open, whereas for sufficiently high density, there is enough gravity to close it back on itself. The "critical density" is that required to barely close the Universe, that is, to render it flat and Euclidean. The critical density depends on the expansion rate, and for the current Hubble constant is close to 10^{-29} (1/[1 with 29 zeros]) grams per cubic centimeter. The degree of closure is expressed by Omega = (actual density)/(critical density). If Omega is less than 1, the Universe is closed; if greater than 1, it is open; if 1, it is flat.
5. In traditional cosmology, Omega determines the fate of the Universe. If Omega is greater than 1, there is enough gravity to halt the expansion and to cause the Universe someday to collapse on itself, the process perhaps recurring in perpetual renewal. If Omega is less than 1, the Universe will expand forever. If Omega is exactly 1, the expansion will coast to a stop, but only after an infinite period of time. The observations of the density of matter, including dark matter, all lead to Omega well under 1.
6. However, Nature is not traditional. Observation of distant Type Ia supernovae, which allow the exploration of the Hubble constant at great distances from Earth, reveal that the expansion is not slowing down, but is accelerating, the expansion getting ever faster as a result of some kind of "dark energy," which, as we will see, has a powerful effect on our view of Omega, positioning it at close to 1.

D. **The Big Bang**

1. Irrespective of Omega, or our ignorance of the actual origin of the Universe, we can still chart the course of the Big Bang. It all began as energy, and the forces of nature were merged into one. Immediately after the initial Big Bang, the early Universe (far less than 1 second old) underwent a short, but intense, "inflationary period" in which space expanded with an extraordinary speed sufficient to flatten it out and to render Omega = 1. The forces of nature then began to separate from each other. After a millionth of a second, with the temperature down to 10 trillion degrees Kelvin, much of the expanding energy had cooled into normal matter (according to Einstein's $E = Mc^2$), into protons and neutrons that were carried along with the now-slowed expansion.
2. Within about three minutes, with the temperature down to a billion Kelvin, protons and neutrons began to fuse to deuterium (hydrogen-2), helium (both helium-3 and normal helium-4), and a bit of lithium. Unlike the core of a star, in which the temperature for a time climbs with age, allowing further fusion, in the expanding Big Bang the temperature was dropping, which quenched further fusion, leaving the Universe with nothing other than these three elements. Primitive stars and stellar systems show the mix of elements and isotopes predicted, powerfully supporting the theory.
3. With the temperature still high, the expanding gas was still ionized, which caused it to interact strongly with the intense radiation still present. After about 400,000 years, the temperature had dropped to a critical

3000 Kelvin, at which point protons could keep electrons bound to them, rendering the gas neutral, which allowed the radiation to run free. Here is the origin of Cosmic Background Radiation, which has been “cooling” for the past 13.7 billion years until it is now at just under 3 degrees Kelvin. The gas of the expanding Universe then turned “dark,” generating no energy on its own.

4. A hundred million years later, the expanding matter began to condense and to form the first generation of stars. Here, little is clear. Massive hot stars consisting of only hydrogen and helium may have formed first. Their explosions salted the star-forming matter with the first heavy elements, allowing the formation of dust and leading to the kind of star formation we have today. Ancient, low-metal stars have just the chemical compositions that we would expect from having their matter contaminated from such explosions. There may have been no low mass “zero-metal” stars, explaining their puzzling absence.

5. The first stars may have formed the nuclei from which galaxies could grow. Early supermassive black holes made the galaxies’ cores, and are now seen as quasars. As heavy elements were built as a result of stellar evolution, mergers of early, immature galaxies formed the grand systems we see today. Observations with the Hubble Space Telescope show that ultradistant galaxies, seen as they were billions of years ago, appear primitive and unformed.

E. **Ripples in the Stream**

1. The Cosmic Background Radiation is incredibly smooth. With great refinement, however, we see it break into ripples with temperature fluctuations of a hundred-thousandth of a degree. The size and number of the fluctuations, analyzed in terms of the theory of the Big Bang, reveal a host of cosmic parameters. From these data, the age of the Universe is 13.7 billion years, which fits nicely with the data found from globular clusters and the Hubble constant of 22 kilometers per second per million light years found from direct observation of galaxy motions.
2. As expected from theory (to be even near 1 now, Omega HAS to be 1), the ripples show that Omega is indeed equal to 1 and that the Universe is flat. Since mass and energy are two sides of the same thing, both have the ability to close and flatten the Universe. Different constituents of the Universe contribute different fractions to Omega. “Bright matter” (stars and the classical interstellar medium) contribute no more than 0.7 percent! About six times as much (four percent) is tied up in normal matter, most of which is difficult to observe (intergalactic gas and so on), in agreement with X-ray observations and that needed for the Big Bang to create the primordial deuterium, helium, and lithium we find today. Nearly a quarter (23 percent) of the substance of the Universe is in the form of “cold dark matter” of unknown form. The overwhelming majority, 73 percent, is in the form of this even more-mysterious “dark energy,” the amount agreeing nicely with that found from the acceleration of the Universe using Type Ia supernovae.

F. **And at the End...**

While mystery abounds (and delightfully so, else there would be no science to pursue), we have so much agreement from different observations that we can only believe that the Big Bang really happened. We, our Earth, and ourselves are the product of it all, from the Big Event, through the first stars and galaxies, to the later generations of stars that made the heavy elements that led to the star formation of today, to the Sun and Earth itself. In spite of the uncertainties, we can look outward into the sky and trace the path of creation from the moment that space began to expand right down to the flowers in the garden. What happened before the Big Bang we may never know. We may never know either of the possible existence of other universes that we cannot contact, of other Big Bangs within an infinity of infinities. At the end, the most remarkable thing is that we can think about it, and maybe even truly understand a small part of the extraordinary place that Nature has given us.

FOR GREATER UNDERSTANDING

Questions

1. Summarize the evidence for the reality of the Big Bang.
2. What is the nature of the Cosmic Background Radiation, and what can be found from it?
3. Trace the path of the evolution of the Universe from the beginning to the creation of the Earth.

Suggested Reading

Lederman, L.M. and Schramm, D.N. *From Quarks to Cosmos: Tools of Discovery*. Scientific American Library. New York: Freeman, 1989.

Other Books of Interest

Ferris, Timothy. *The Whole Shebang*. New York: Touchstone Books, Reprint, 1998.

Harrison, E.R. *Cosmology*. Cambridge: Cambridge University Press, 1981.

Silk, J. *A Short History of the Universe*. Scientific American Library. New York: Freeman, 1994.

Websites to Visit

1. http://cosmology.berkeley.edu/Education/IUP/Big_Bang_Primer.html - Big Bang Primer
2. http://map.gsfc.nasa.gov/m_uni.html - the Big Bang
3. http://archive.ncsa.uiuc.edu/Cyberia/Cosmos/InTheBeginning.html - the Big Bang
4. http://www.pbs.org/deepspace/timeline/ - the Big Bang
5. http://image.gsfc.nasa.gov/poetry/ask/acosmexp.html - Big Bang questions
6. http://map.gsfc.nasa.gov/m_mm.html - cosmic background ripples

COURSE MATERIALS

You'll get the most out of this course if you have the following book:

Kaler, James. *Astronomy! A Brief Edition*. New York: Addision-Wesley, 1987.

Suggested Reading

Ferris, Timothy. *Coming of Age in the Milky Way*. New York: Anchor, Reprint, 1989.

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Lang, K.R. *The Cambridge Encyclopedia of the Sun*. Cambridge: Cambridge University Press, 2001.

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Naeye, R. *Through the Eyes of Hubble: The Birth, Life, and Violent Death of Stars*. Wisconsin: Kalmbach, 1997.

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