Astrophysics II

Spring Term 2001

Lecture 1 : Background : from the big bang to stars and galaxies

The Universe is thought to have been created in the **Big Bang**, in which space and time were created in a simple hot energetic, state, about 15 billion (15 x 10^9) years ago.

Five steps from the Big Bang to Stars

Step 1) During the first 10^{-43} seconds the four fundamental forces are unified (although no complete physical description of this era yet exists). Temperature 10^{32} Kelvin. 10^{-43} seconds defines the time when gravity splits from the other forces (weak, strong and Electro-magnetic).

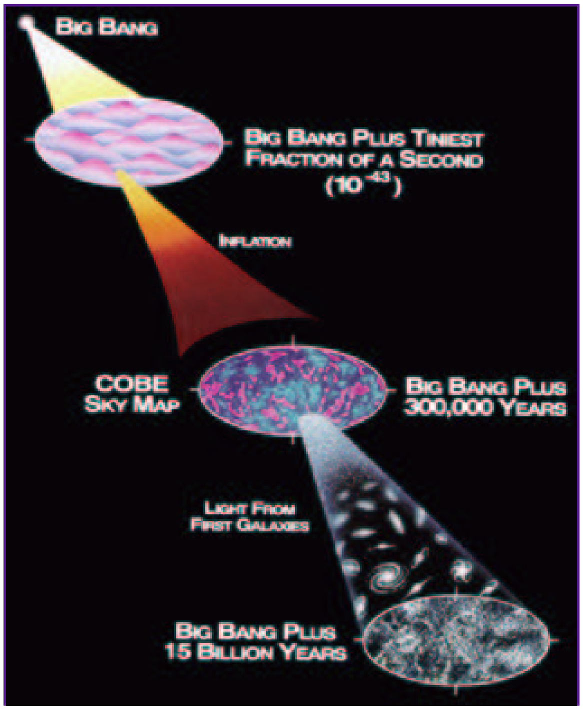
Step 2) Up to 10^{-35} seconds, quarks and anti-quarks dominate the Universe. The strong force separates from the weak and electromagnetic forces. Temperature drops to 10^{27} Kelvin. At 10^{-12} seconds the four forces become distinct.

Step 3) At 0.01 seconds, electrons and positrons form as the temperature drops to 10^{11} Kelvin. After 1 second, the Universe becomes transparent to neutrinos, which from now on hardly interact further with matter.

Step 4) At three minutes after the big bang, the temperature has reached 10^9 K, protons and neutrons combine to form what will become the nuclei of elements mostly H and He). After 300,000 years the temperature has dropped to 3000 K and the electrons are captured by nuclei to form neutral atoms. The Universe becomes transparent to light (photons stop interacting with free electrons) resulting in the formation of the **Cosmic Background Radiation**.

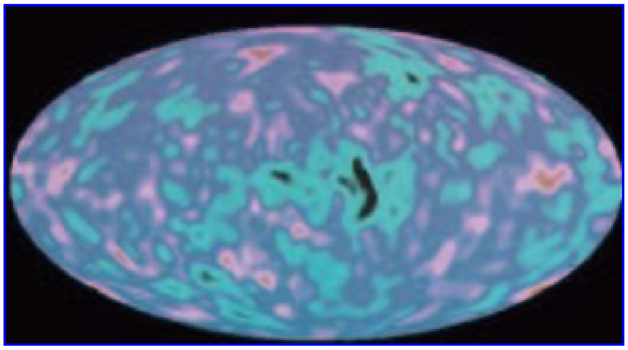
Step 5) After 1 billion years, the temperature is 20 K and galaxies and stars have begun to form via gravitational contraction of over-densities in the initial Universe. Af a few billion years our Galaxy forms, at about 10 billion years after the Big Bang the Sun and Earth form. After 15 billion years we reach the present and a background temperature of about 3 K.

Adapted from "Steven Hawking's Universe" http://www.pbs.org/wnet/hawking/universes/html/univ.html



Source: http://www.seas.columbia.edu/~ah297/un-esa/universe/universe-chapter5.html
Encyclopedia of Applied Physics, Vol. 23 (Page 47 - 81), 1998 WILEY-VCH Verlag GmbH, ISBN: 3-527-29476-7

About 300,000 years after the Big Bang, there was the era of **recombination** in which protons and electrons combined to form neutral Hydrogen. At this point, baryonic matter in the Universe consisted of about 75% Hydrogen and 25% Helium (by mass), with some small amounts of **heavy elements** (elements starting from Lithium). The distribution of this material was very close to, but not quite, uniform. These slight over- and under-densities were observed for the first time by the COBE satellite (launched in 1989) and amount to only a few parts in 100,000. The variations were mapped out over the whole sky, shown in the next figure, on scales of greater than about 7 degrees.

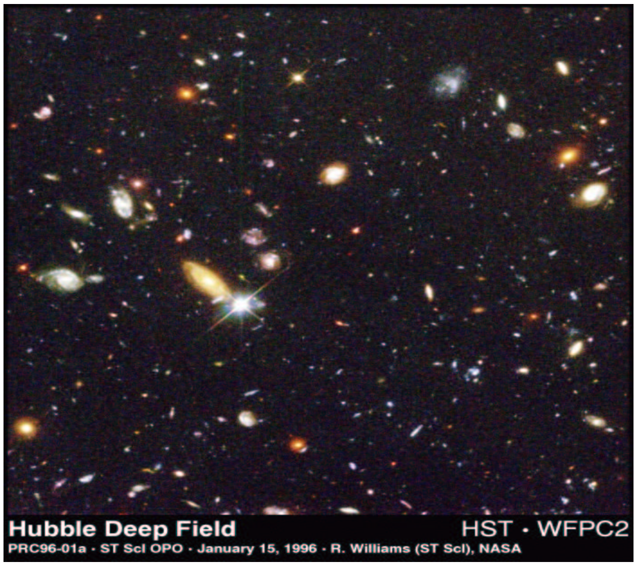


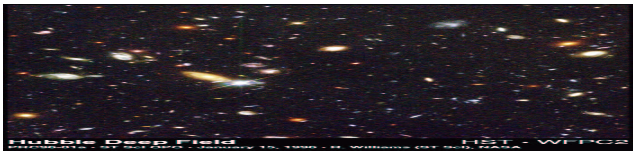
Source: http://www.seas.columbia.edu/~ah297/un-esa/universe/universe-chapter5.html
Encyclopedia of Applied Physics, Vol. 23 (Page 47 - 81), 1998 WILEY-VCH Verlag GmbH, ISBN: 3-527-29476-7

After recombination, the Universe entered a period called the "Dark Ages", until gravitational attraction had operated on very slight overdensities in the matter distribution, leading to the **formation of light emitting stars and galaxies**. Did the formation of early stars and galaxies take place "top-down" or "bottom up"? i.e. did the stars form first and get together to form galaxies? Or did the gas collect together into galaxy like objects first and then develop stellar structure? Most people would answer "bottom-up" these days -- the HST images of lumpy galaxies in the distant universe seem to suggest that galaxies formed from many sub-units. The development of stars and other sources of light meant the Universe was optically observable again!

Exactly how stars and galaxies formed, when the process started and how long it took is currently a major area of research. A simple picture runs like this: about 1 billion years after the big bang the first star forming regions, conglomerates of perhaps 10^6 to 10^9 solar masses began to develop. Over the next several billion years, most of these merge to form larger units or are partially destroyed by the energetic supernovae which develop as a natural part of star formation. Within a few billion years most of these have developed into stable configurations of stars and gas and are recognisable as "galaxies".

The faintest galaxies so far observed were seen in the "Hubble Deep Field", a tiny patch of sky which was imaged for more than a week by the Hubble Space Telescope. Part of this image is shown below ---



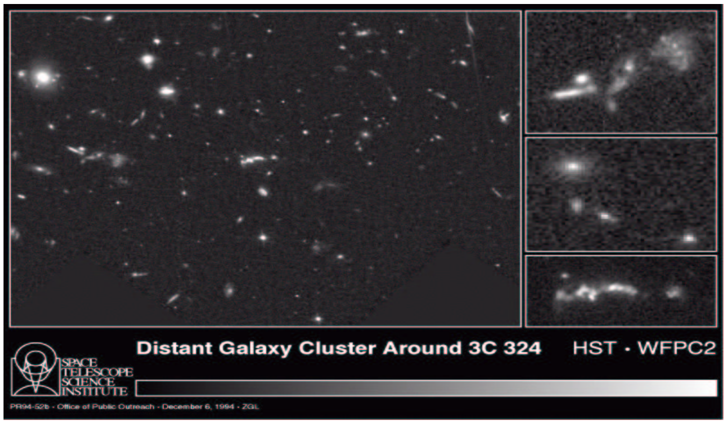


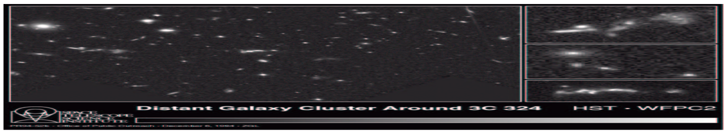
Galaxies have been identified in this image with redshifts which indicate that the light reaching us has been travelling for about 90 percent of the age of the Universe --- or about 12-15 billion years. One such galaxy is shown below --- this must have been amongst the very first galaxies (and the stars in it) which formed ...

These galaxies are at present too few in number and too faint to be study in the kind of detail which we would like --- to allow us to answer basic questions concerning exactly when and and what conditions the stars formed. However, a new generation of 10 meter class telescopes is currently coming on line all around the world so these issues are among those which these telescopes will concentrate.

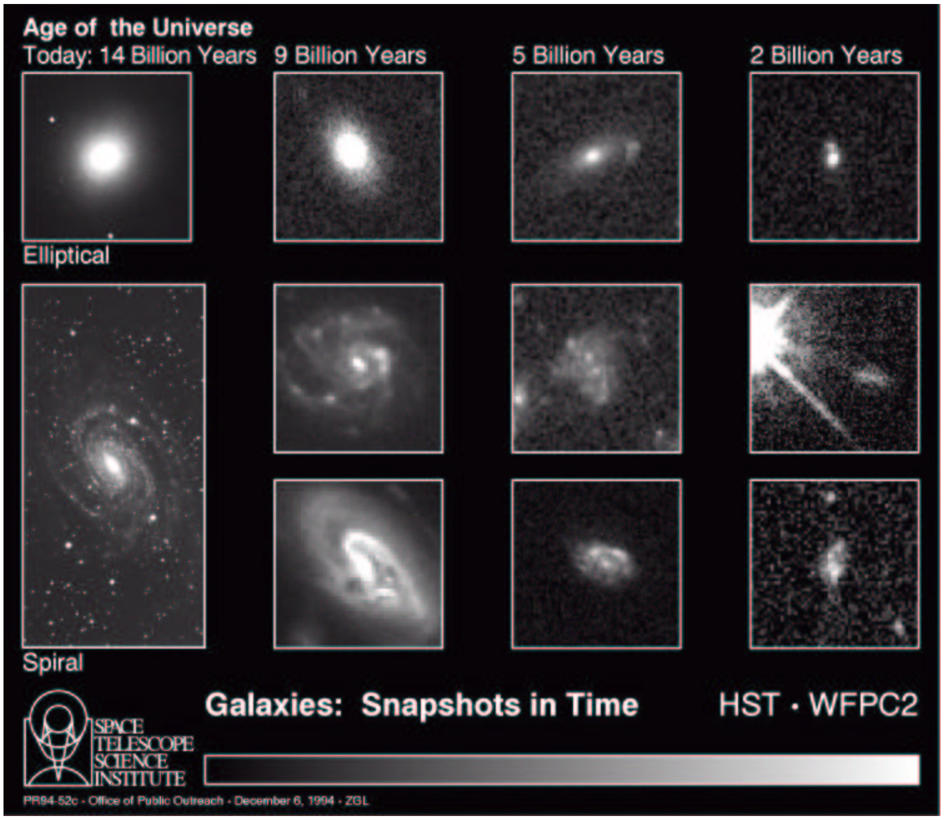
The last 10 billion years or so of the developments in galaxies and in their stellar content is now quite well studied because of the

Hubble Space Telescope, which was able to obtain clear images of these distant galaxies for the first time. The following picture shows early galaxies in the (confused) process of forming. One shouldn't forget that these knots of light are due to billions of stars forming, more or less at the same time...



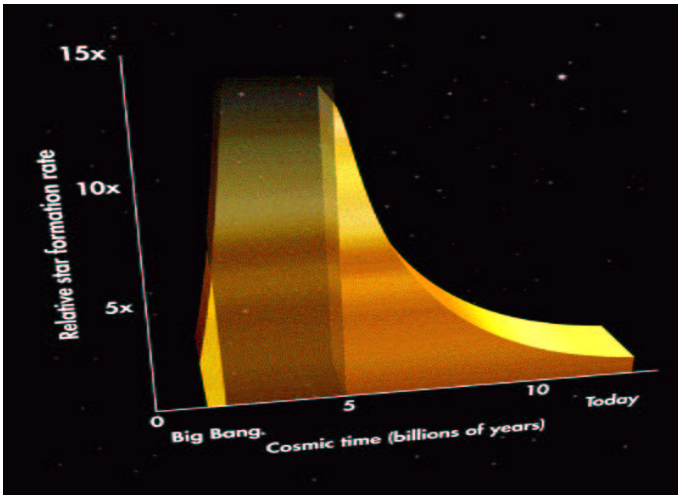


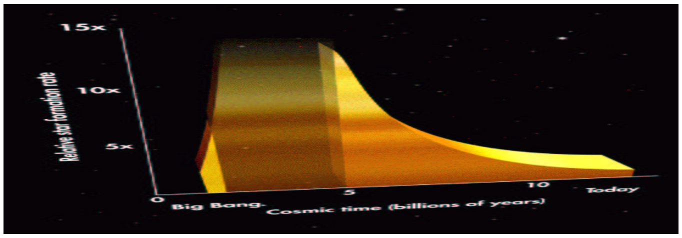
A sequence of galaxy images as a function of time runs like this :



The general picture is that galaxies have been forming over quite a few billion years, are continuing to form and develop still, and seem to have been assembled from many smaller sub-galaxies.

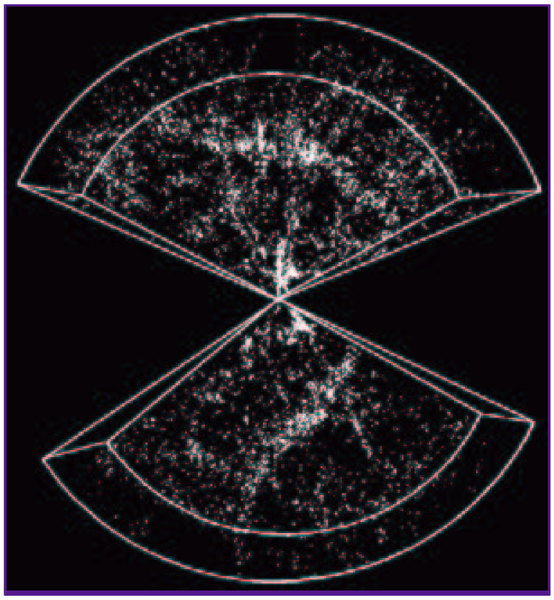
Probably most of the "mature" galaxies we see around us now originate from this epoch 10-12 billion years ago. Classically (20 years ago) it was considered that most or all galaxies had formed at this time. However, several studies now show that galaxy formation is an on-going process, but at a much reduced rate. The plot below is a recent estimate of the rate at which stars have formed (in galaxies) over the lifetime of the Universe.





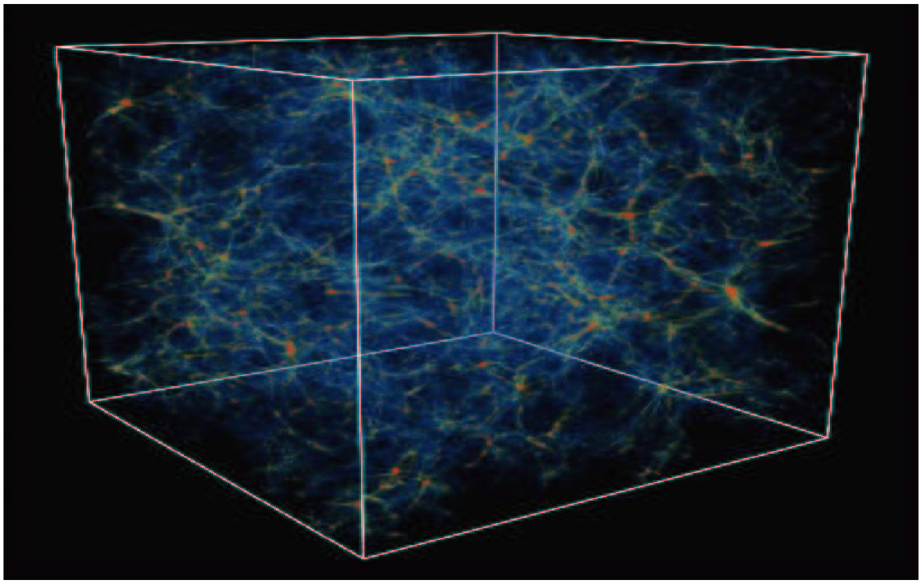
Source http://oposite.stsci.edu/pubinfo/pr/96/37.html

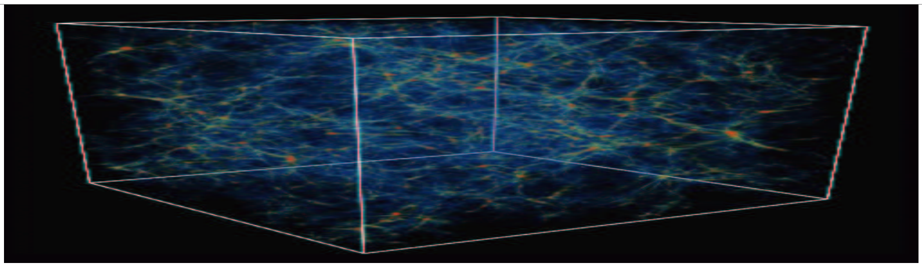
The distribution of galaxies in space around us in the nearby Universe is currently a very active research area. Recent surveys have revealed a very detailed foamy structure in which galaxies are found along "walls" surrounding large "voids" which are relatively galaxy free. The precise form of this distribution places interesting constraints on the type of Universe we inhabit --- its total mass, expansion rate and ultimate fate.



A map of the nearby Universe --- some 9300 galaxies each represented by a dot. The survey shows two slices across the sky plotted against the redshift (or indirectly, distance) of each galaxy. Several large structures (walls) can be clearly seen as well as large voids where galaxies are relatively absent.

Source: http://www.seas.columbia.edu/~ah297/un-esa/universe/universe-chapter5.html
Encyclopedia of Applied Physics, Vol. 23 (Page 47 - 81), 1998 WILEY-VCH Verlag GmbH, ISBN: 3-527-29476-7
Margaret J. Geller, John P. Huchra, Luis A. N. da Costa, and Emilio E. Falco, Smithsonian Astrophysical Observatory © 1994





Surveys like the one above map the local Universe by measuring the position in 3-D space of galaxies up to a few hundred Mpc away. The observable Universe has a diameter of order 10 Gpc. To find and observe galaxies at large distances (and therefore in the early Universe) requires large or special telescopes. The formation of galaxies is not well understood, although the field is beginning to open up. The figure above shows the start of the art at present, in which galaxies have formed in a computer simulation of the gravitational collapse of the initial perturbations which came from the big bang. The simulations are difficult to compute because the effects of gas dynamics and star formation in the forming galaxies is very poorly understood.

Galaxy Morphology

Quite a number of schemes have been developed to classify galaxies by their shape (or morphology). These schemes are really only descriptive, and have become less useful in very recent times as the Hubble Space Telescope has revealed that many (possibly most) distant galaxies are chaotic sites of star formation which defy simple descriptive classification.

Nearby galaxies can be very usefully classified as *spiral*, *elliptical* or *irregular.*

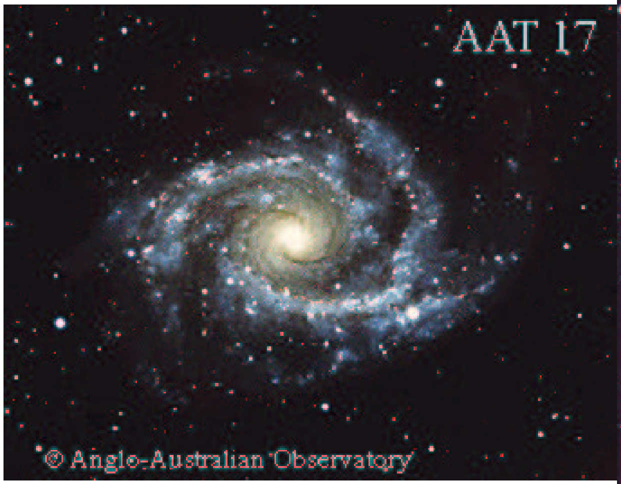
- SPIRAL galaxies have fast rotating, flattened disks, and contain some gas and dust.
- ELLIPTICAL galaxies are slowly rotating ellipsoids, usually containing little gas and dust.
- IRREGULAR galaxies have no simple shape, and usually contain a lot of gas and dust.

Source http://www-astronomy.mps.ohio-state.edu/~ryden/ast162_7/notes28.html

Spiral Galaxies

Spiral galaxies have rotationally flattened disks, and contain moderate amounts of gas and dust.

Our own galaxy is a spiral galaxy; so is the Andromeda Galaxy (M31), and the Whirlpool Galaxy (M51).



AAT17 - NGC 2997: Sc galaxy, seen face-on.

INT4 - NGC 892: Sb galaxy, seen edge-on.

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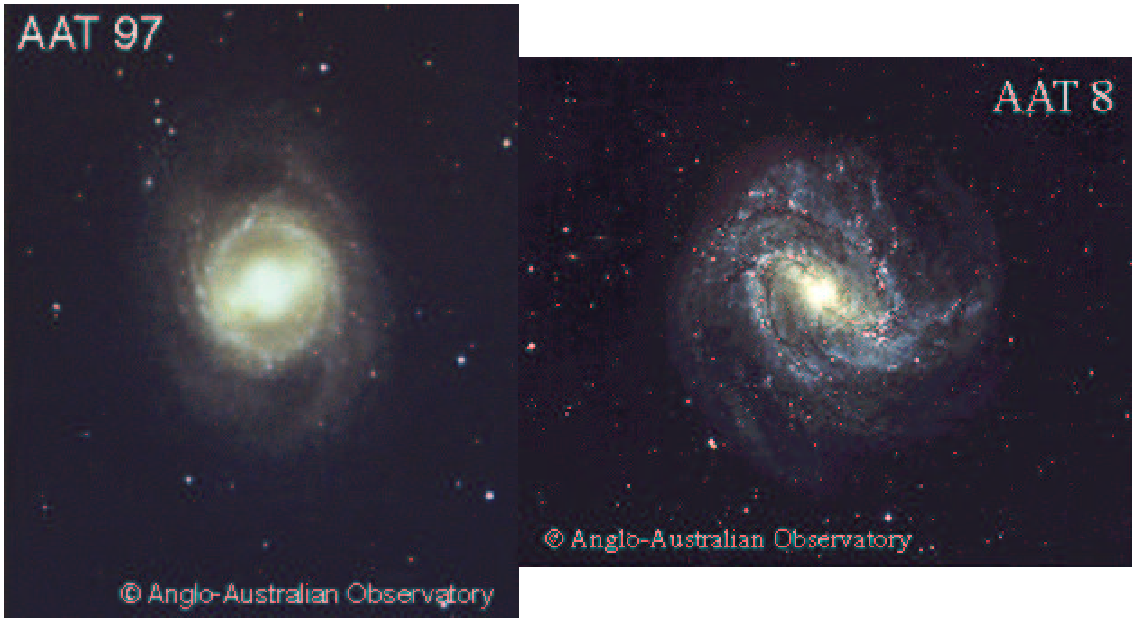
Source http://www.aao.gov.au/images.html

All spiral galaxies have

- flat, rotating disks
- central bulges
- gas and dust in the disk
- star formation in spiral arms

A ‘‘subspecies’’ of spiral galaxy is the class of barred spirals. In a barred spiral galaxy, the spiral arms wind away from an elongated central bar rather than from a spherical central bulge.



AAT 97 - NGC 3351: SBb galaxy
AAT 8 - M83: SBc galaxy

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Source http://www.aao.gov.au/images.html

Elliptical Galaxies

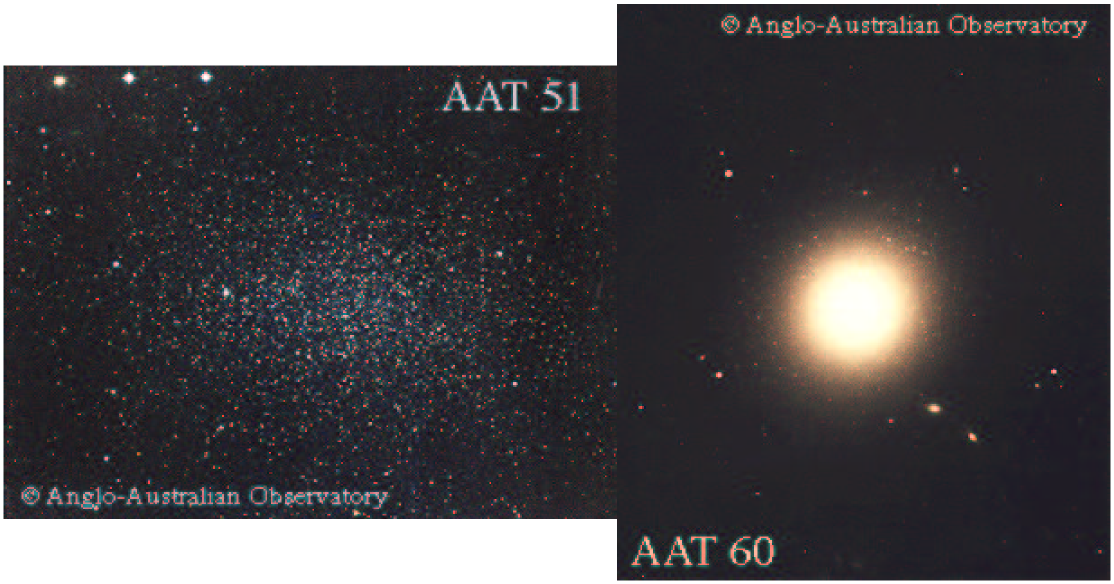
Elliptical galaxies are slowly rotating ellipsoids, and contain little gas and dust.

Elliptical galaxies are actually the most common type of galaxy. Randomly select a large number of (nearby -- within a few 100 Mpc) galaxies. On average, you will find:

- 60% elliptical
- 20% spiral
- 20% irregular

Elliptical galaxies contain very little gas and dust, and the gas that is present is very hot and diffuse. Consequently, there is no current star formation in elliptical galaxies. The stars in elliptical galaxies are old (termed "Population II") stars. Unlike the disks of spiral and S0 galaxies, elliptical galaxies are NOT rotating rapidly.

Elliptical galaxies have a very large range of sizes. Both the largest and smallest galaxies in the universe are elliptical. Giant elliptical galaxies contain 1 trillion stars or more. Dwarf ellipticals contains 10 million stars or less.

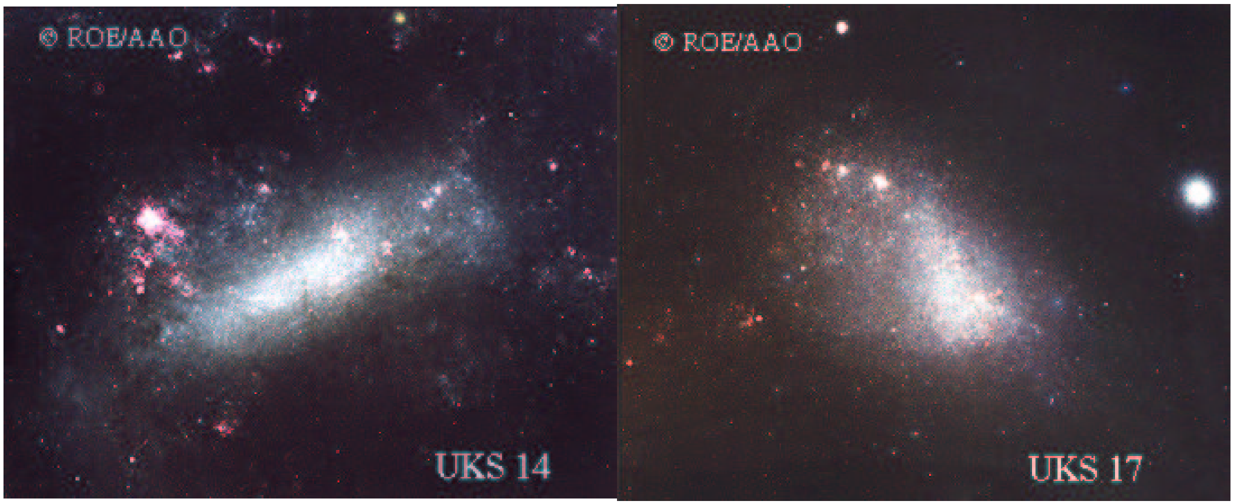


The images show the giant elliptical galaxy M87 (which is about 200 kiloparsecs in diameter, 10 times the Mily Way) and the dwarf elliptical galaxy Leo II (which is about 1 kiloparsec in diameter, and contains so few stars you can see right through it). Of the two dozen galaxies closest to us, a dozen are dwarf ellipticals.

© Anglo-Australian Observatory
Source http://www.aao.gov.au/images.html

Irregulars

These galaxies are irregular in shape and dynamics. They contain lots of gas and dust; in extreme cases, as much as 90% of the total mass of an irregular galaxy is in the form of interstellar gas and dust. As a consequence, irregular galaxies contain copious star formation. The star formation is patchy (tending to occur in clusters), as is the distribution of dust. Therefore, irregular galaxies are given their characteristic irregular, patchy, raggedy appearance. The Large and Small Magellanic Clouds, about 50,000 parsecs away from our own galaxy, are examples of irregular galaxies.

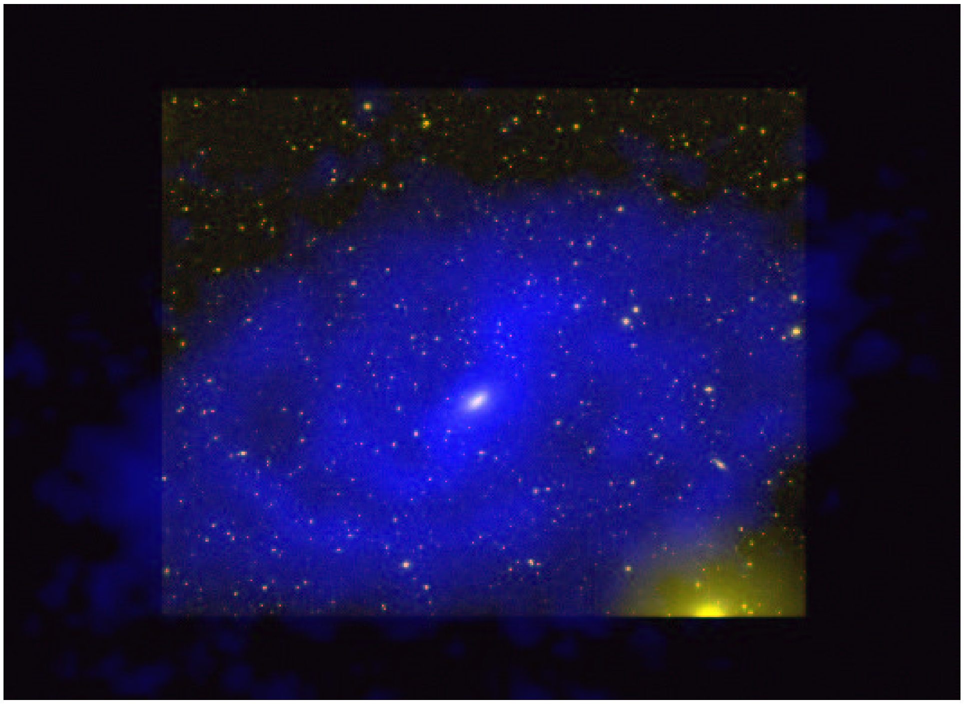


UKS 14 - The Large Magellanic Cloud
UKS - 17 The Small Magellanic Cloud.

© Anglo-Australian Observatory
Source http://www.aao.gov.au/images.html

The gas, stars and dust content of the galaxy types mentioned above may not be the final word. For example, one recently discovered spiral galaxy consists almost entirely of gas with a very tiny central region containing stars. It is worth keeping in mind that there are probably still a few surprises out there.

This image shows the radio and optical maps overlayed for the galaxy NGC 2915. Blue is the radio map, yellow is the optical. This is probably a "failed" galaxy which has not (yet) turned from gas to stars.



Source http://www.atnf.csiro.au/~bkoribal/n2915.html
Gerhardt Meurer (Johns Hopkins University)

Further superb images of Galaxies sorted by type can be found at the Anglo Australian Observatory (http://www.aao.gov.au/local/www/dfm/galaxies.html).

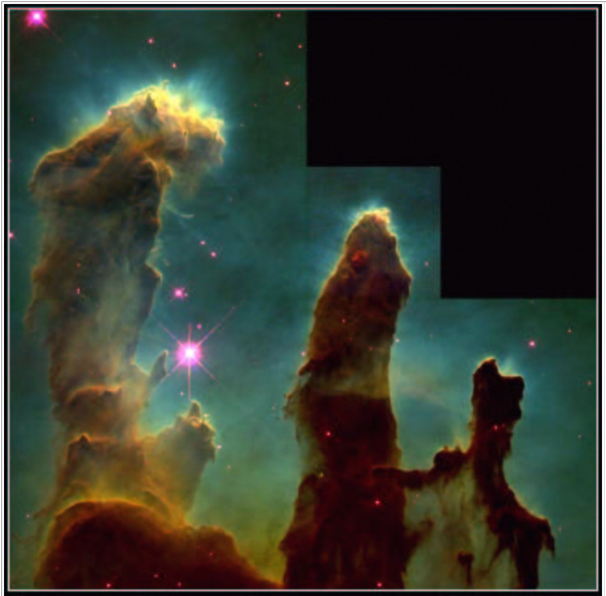
Star Formation

In these proto-galactic units the dominant process is that of **star formation** itself. We know that star formation takes place in giant collapsing clouds of gas, and can take place under a wide range of circumstances which result in stars being formed at a slow rate (such as most nearby regions of star formation in our own galaxy) or hundreds to thousands of times faster (such as in the compressed gas clouds which result when galaxies are disturbed or actually collide). However, the process by which clouds actually fragment and collapse into individual stars has long been a very poorly understood area of Astronomy, and remains almost as obscure today as it was 30 years ago. This is an area of research whose time has not yet come!

Hubble has revealed higher resolution images of star forming regions, which at least show some of the complexities of the physical processes involved...

Star-Birth Clouds · M16 HST · WFPC2

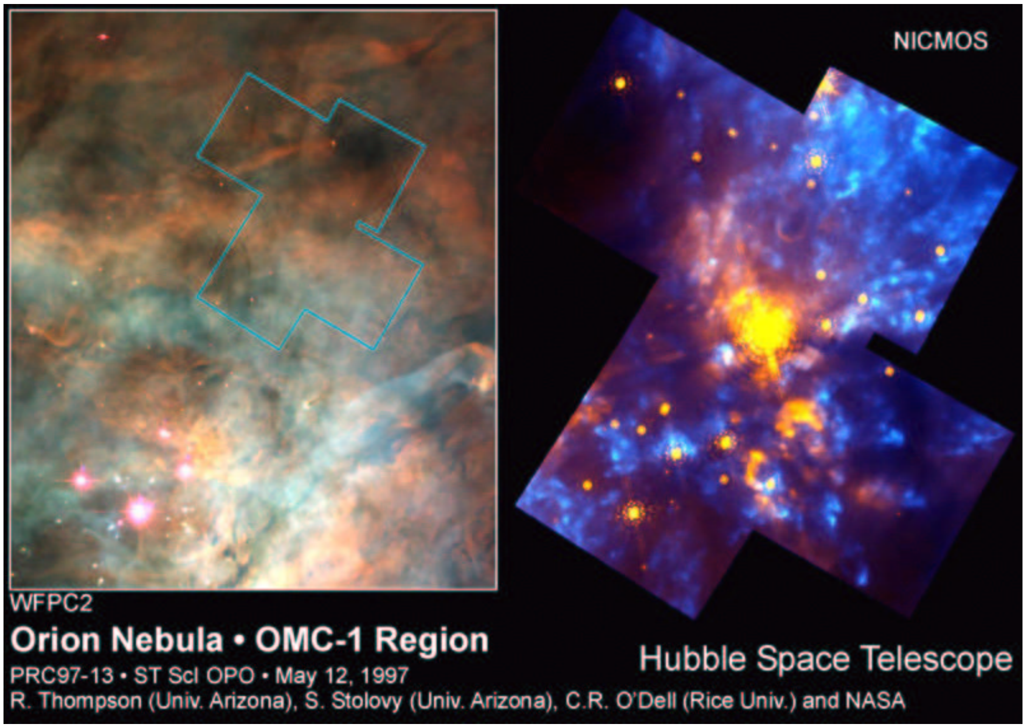
PRC95-44b · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA



Gaseous Pillars · M16 HST · WFPC2

PRC95-44a · ST ScI OPO · November 2, 1995
J. Hester and P. Scowen (AZ State Univ.), NASA

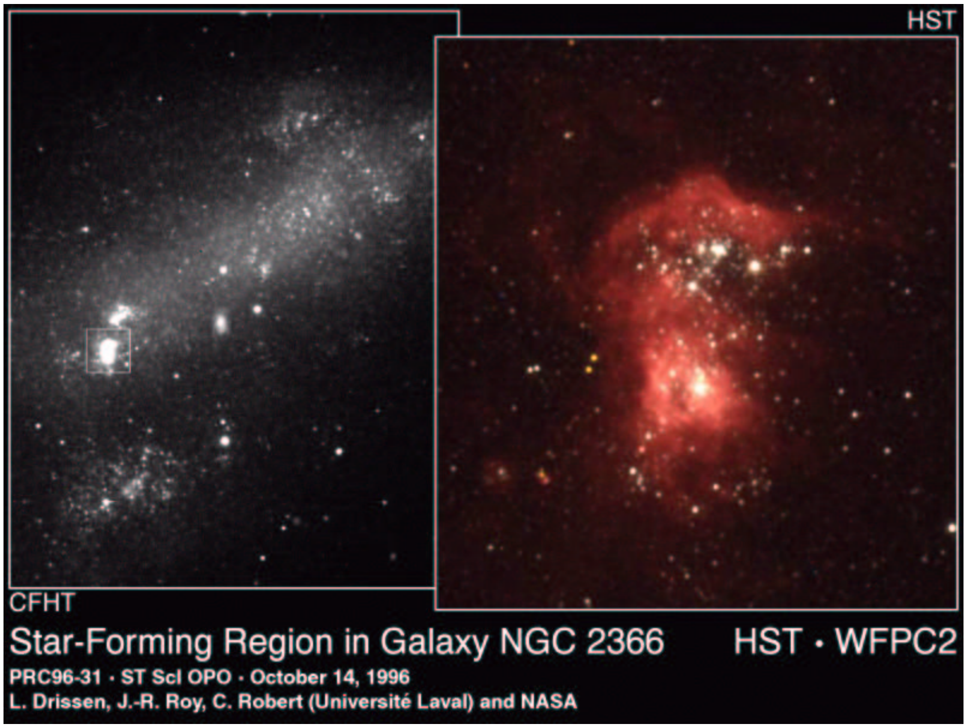
The pictures above show columns of cool interstellar hydrogen gas and dust that are also incubators for new stars. The pillars protrude from the interior wall of a dark molecular cloud like stalagmites from the floor of a cavern. They are part of the "Eagle Nebula" (also called M16), a nearby star-forming region 7,000 light-years away in the constellation Serpens. The pillars of gas are dense gas which has survived being "eroded" away by the light of hot UV stars nearby, and the small blobs are even denser regions where it is very likely that stars themselves are actually forming. They'll emerge from the cocoons in which they are incubating millions of years rom now, and for the moment are so heavily shrouded by dust that we cannot see them at all with optical light. Infrared light (heat) which does escape from the regions is the main clue that energetic processes are taking place. The image below shows how different imagesin optical (on the left) and infrared (on the right) taken of the same region in the Orion Nebula can be.



Orion Nebula • OMC-1 Region Hubble Space Telescope

PRC97-13 • ST ScI OPO • May 12, 1997
R. Thompson (Univ. Arizona), S. Stolovy (Univ. Arizona), C.R. O'Dell (Rice Univ.) and NASA

The star forming regions can be very large, sometimes occuping a major section of an entire galaxy, such as seen in the image below ---



Star-Forming Region in Galaxy NGC 2366 HST • WFPC2

PRC96-31 • ST ScI OPO • October 14, 1996
L. Drissen, J.-R. Roy, C. Robert (Université Laval) and NASA

Out of these star forming regions star eventually emerge --- often "en mass" in giant clusters of up to a million stars at once...

30 Doradus

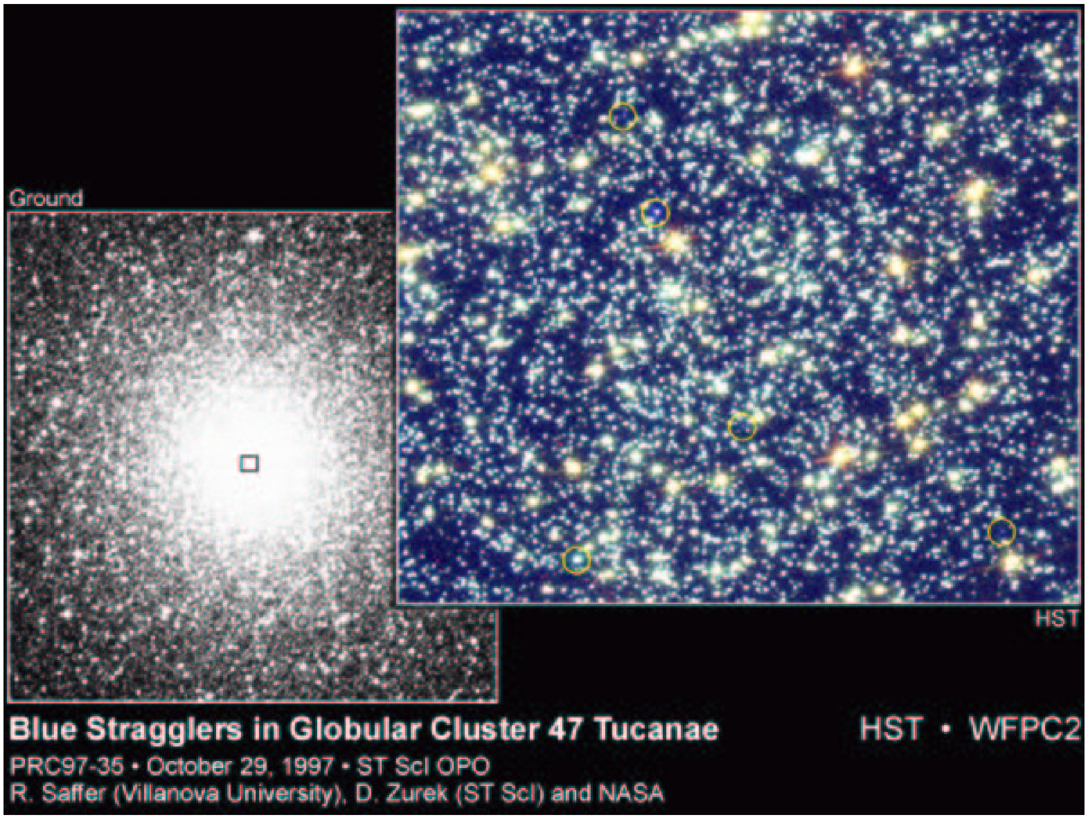
A Giant H II Region around a Dense Star Cluster in the Large Magellanic Cloud

Hubble Space Telescope
Wide Field and Planetary Camera 2

The image above shows R136, a dense cluster of young hot stars at the center of 30 Doradus. The cluster is imaged in the Planetary Camera at full resolution.

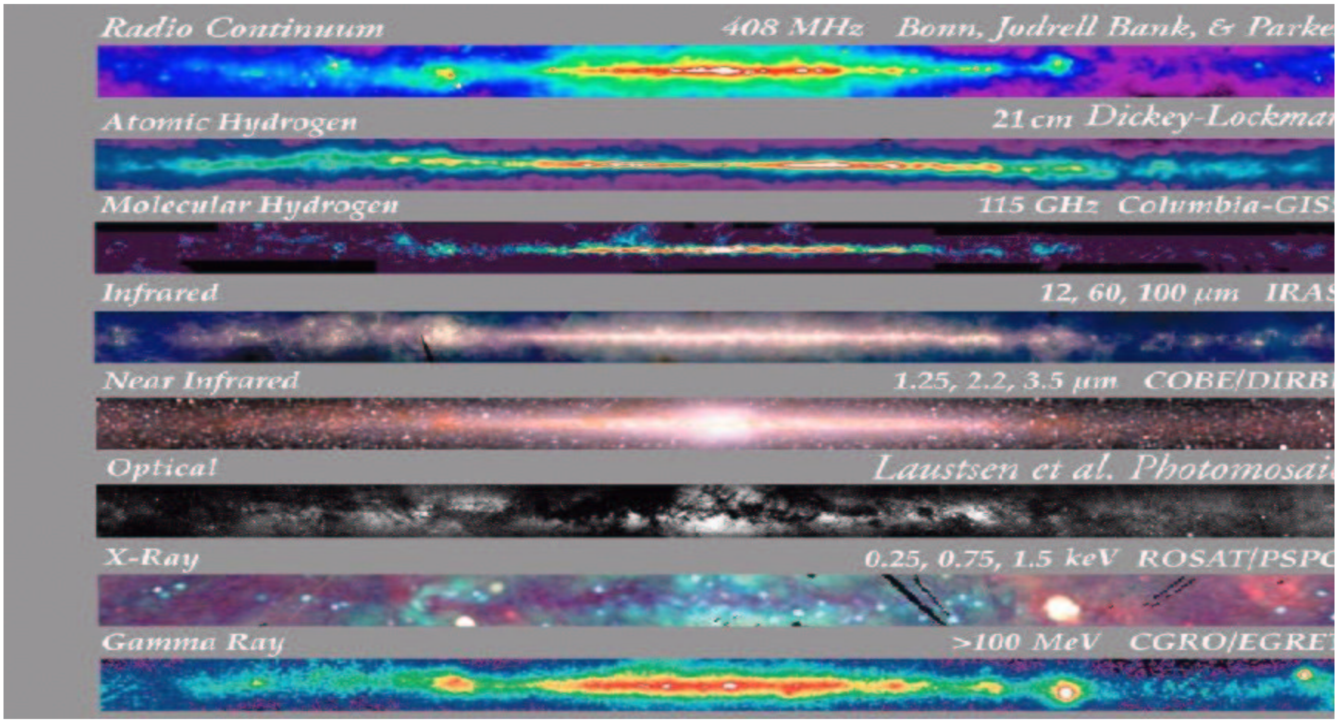
The image at left shows a mosaic of the giant HII region lit up by ultraviolet light from the cluster.

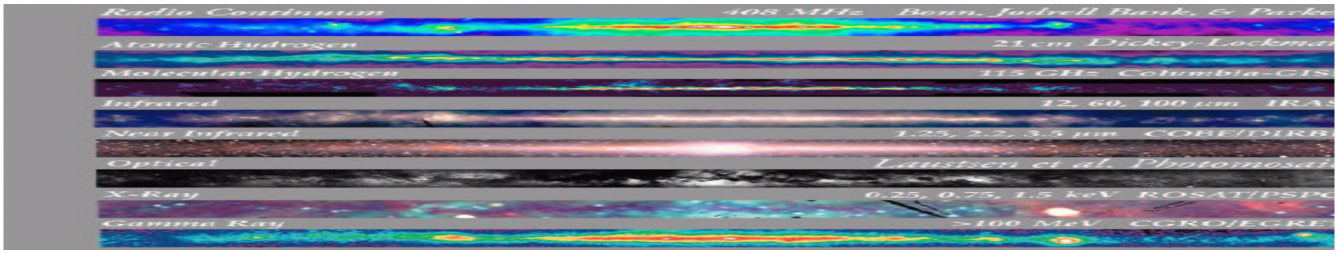
Clusters of stars which we can see forming like this might end up as what we know today as "globular clusters" of our own Galaxy --- millions of stars tightly bound by their own gravity which have survived from the earlist times when our galaxy was forming. The image below shows the globular cluster 47 Tuc, a naked eye object in the Southern Hemisphere, and a zoomed in view taken with the Sapce Telescope of the central regions. Space Telescope was actually capable of resolving the individual stars for the first time (they are too closely packed to resolve individually from ground based telescopes).



Multiwavelength Milky Way

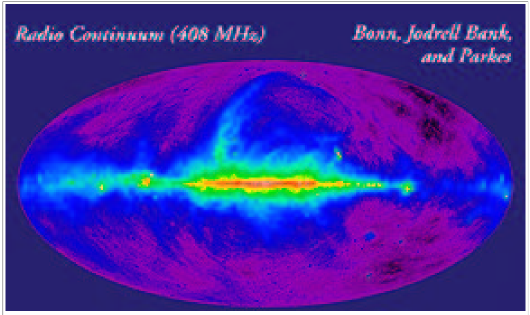
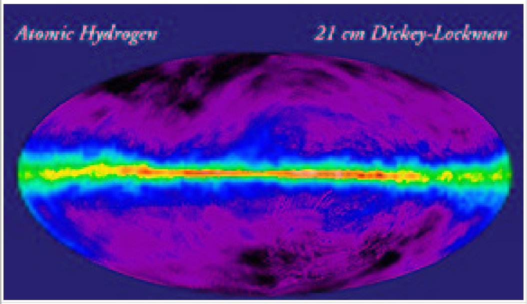
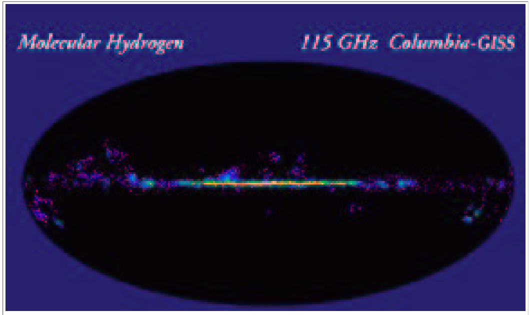
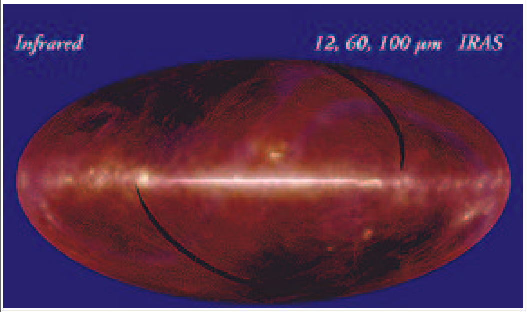
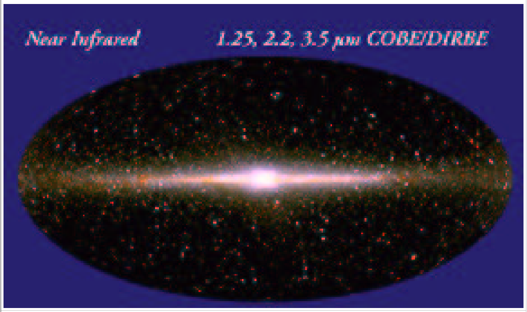
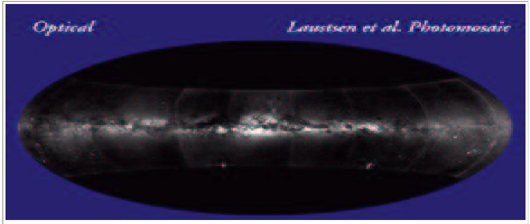
Our view has changed radically in other ways since the 1950's --- in the wavelength of observation!

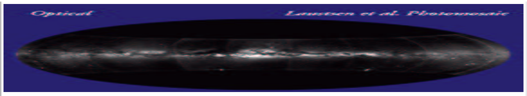


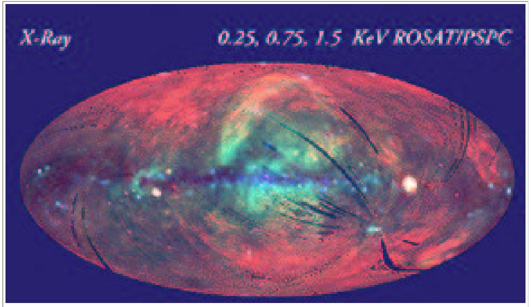


Source http://adc.gsfc.nasa.gov/mw/milkyway.html

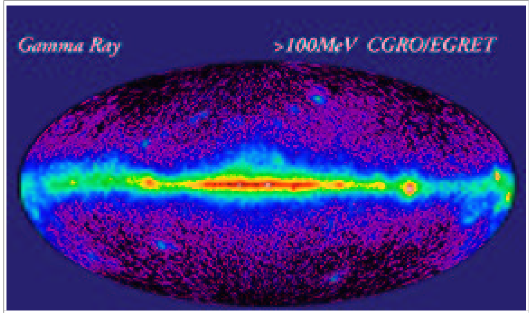
The images above show views of the Milky Way along the Galactic plane over wavelengths from Radio to Gamma.

	Radio map at 408 Mhz, showing mainly emission due to scattering of free electrons in the interstellar plasma (i.e. hot gas). The large arc is due to a nearby supernova remnant.
	21 cm radiation map, showing the distribution of neutral Hydrogen gas in the galactic disk, and a few nearby arcs from recent supernovae.
	Distribution of H2, or molecular Hydrogen.This maps the "cold" gas in the Galaxy, from which stars will eventually form. The actual observed molecule is CO, rather than H2, which is very difficult to detect directly. The star forming layer of gas is remarkably thin.
	Infrared maps at the wavelengths 12, 60 and 100 microns. Infrared emission predominately comes from interstellar dust which is "warmed" to a f ew 10s of degrees Kelvin by the ambient radiation field of the Galaxy’s stars.
	Near Infrared emission is dominated by cool stars. Since these are typically either old or long-lived stars, this is our best view of the Galaxy with the hot, bright young stars removed. Dust absorption at these wavelengths is very low and we get a clear view all the way to the Galactic center of the disk and bulge.
	Optical imageof the Galaxy showing the huge effects that dust absorption has on our view of the central regions of the Galaxy. The emission is dominated by young and old stars and by the effects of dust.





X-ray image taken by the Rosat satellite. This view, less clear than the others is dominated by supernova remnants (some of the arclike features) as well as individual sources of X-radiation from close binary stars or black hole candidates.



Egret’s Gamma ray view of the Galaxy is dominated by emission from Cosmic Rays (high energy particles) decelerating in the interstellar medium.

Review of Stellar Properties

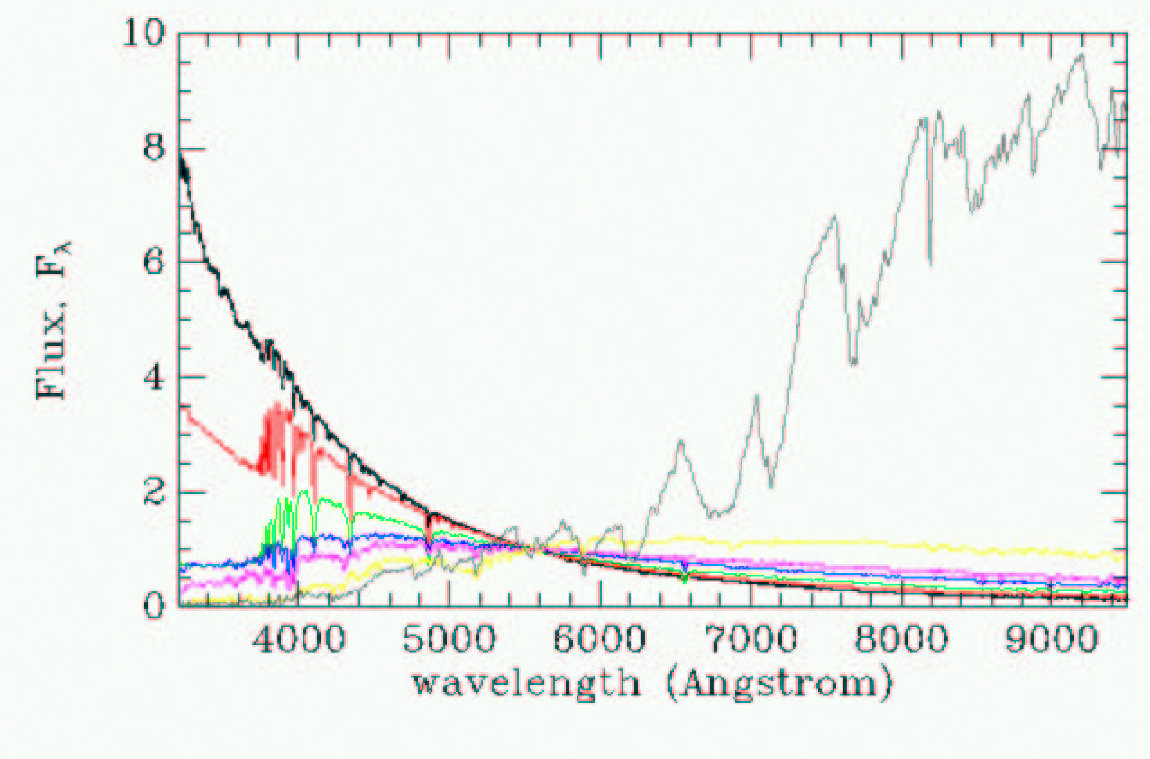
Stars are classified into **spectral types** depending on their colour and characteristics in their spectra.

Spectral Type	Temperatute range	Mass range on the Main Sequence	Lifetimes	Comments
O	60,000-30,000K	20 - 120 M_O	10^5 - 10^6 years	Hot, young and massive - shortest lifetimes, found in young stellar associations
B	30,000-10,000 K	20 - 3 M_O	10^8 years	Like O stars but less extreme; longer lived, less luminous
A	10,000-7,500 K	3 - 1.5 M_O	0.5-1x10^9 years	Typically younger than a few x10^9 years, part of the "Young disk", a thin layer of stars close to the Galactic plane
F	7,500-6,000 K	1.5 - 1 M_O	10^{10} years	Like A stars but longer lived. Ages can often be measured for individual F and G stars
G	6,000-5,000 K	1 - 0.8 M_O	few-10^{10} years	Long lived stars. G, K and M stars form the bulk of the Galactic disk
K	5,000-3,500 K	0.8 - 0.5 M_O	>10^{10} years	Cool stars burning Hydrogen slowly. All K and M dwarfs formed during the Galaxy’s lifetime are still on the main sequence, unlike hotter (OBAFG) stars
M	3,500-2,000? K	0.5 - 0.08 M_O	>10^{11} years	Very cool, dim stars, and very common. Most of the stars in the Galaxy are M dwarfs.

Brown Dwarfs	< approx 2,000 K	< 0.08 M_O	>>10^{11} years	Only recently observed, these are not actually "stars" since they do not burn Hydrogen

Masses from K.R.Lang, "Astrophysical Formulae", Springer Verlag

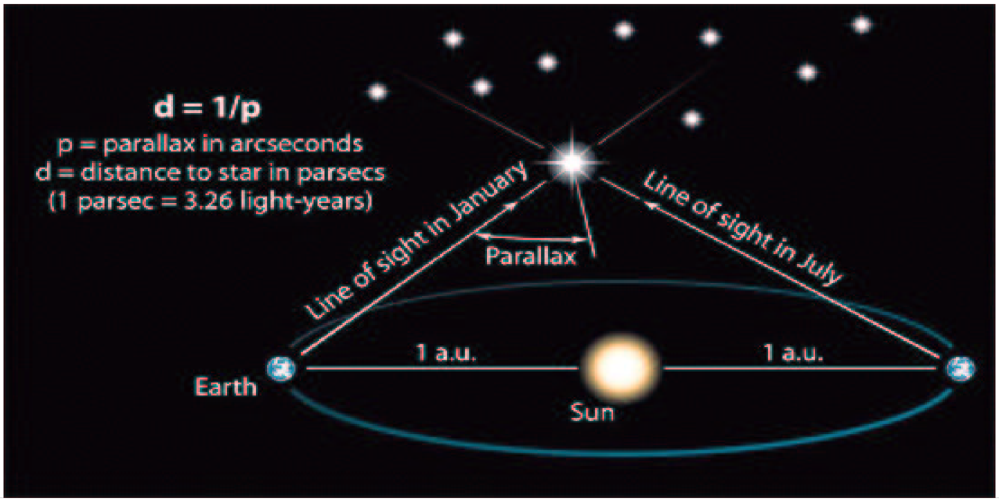
The different spectral types reflect the temperature/mass of the stars. The relative flux distributions as a function of spectral type is shown below. The colours represent : O stars - black, B stars- red, A stars- green, F stars - blue, G stars - purple, K stars - yellow and M stars - grey. (N.B. All spectra normalised to 1.0 at 5500 Angstroms).

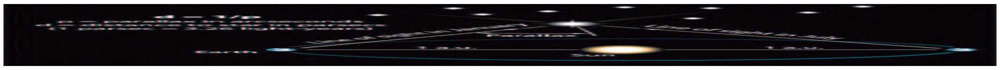


Source http://www.ifa.hawaii.edu/~pickles/hilib.html, (A.J. Pickles, PASP 110, 863, 1998)

Young hot stars are blue, cool stars are red -- as can be easily seen in the amount of blue versus red light put out by stars of different spectra type. The peak in the energy distribution of O + B stars is well into the ultra-violet, while for M stars it is well into the infra-red (off to the left and right respectively on the lower scale). For G type stars like the Sun it peaks just about where our eyes are most sensitive to photons. Note that the spectral distributions shown above are for a star observed outside of the Earth's atmosphere --- the atmosphere can change the distribution markedly in the UV and IR.

Distances to stars can be directly measured via the parallax effect, in which the position of the star changes slightly as the Earth moves around the Sun.
This is the only direct method to measure the distance of stars.





Source http://wwwhip.obspm.fr/hipparcos/SandT/hip-SandT.html

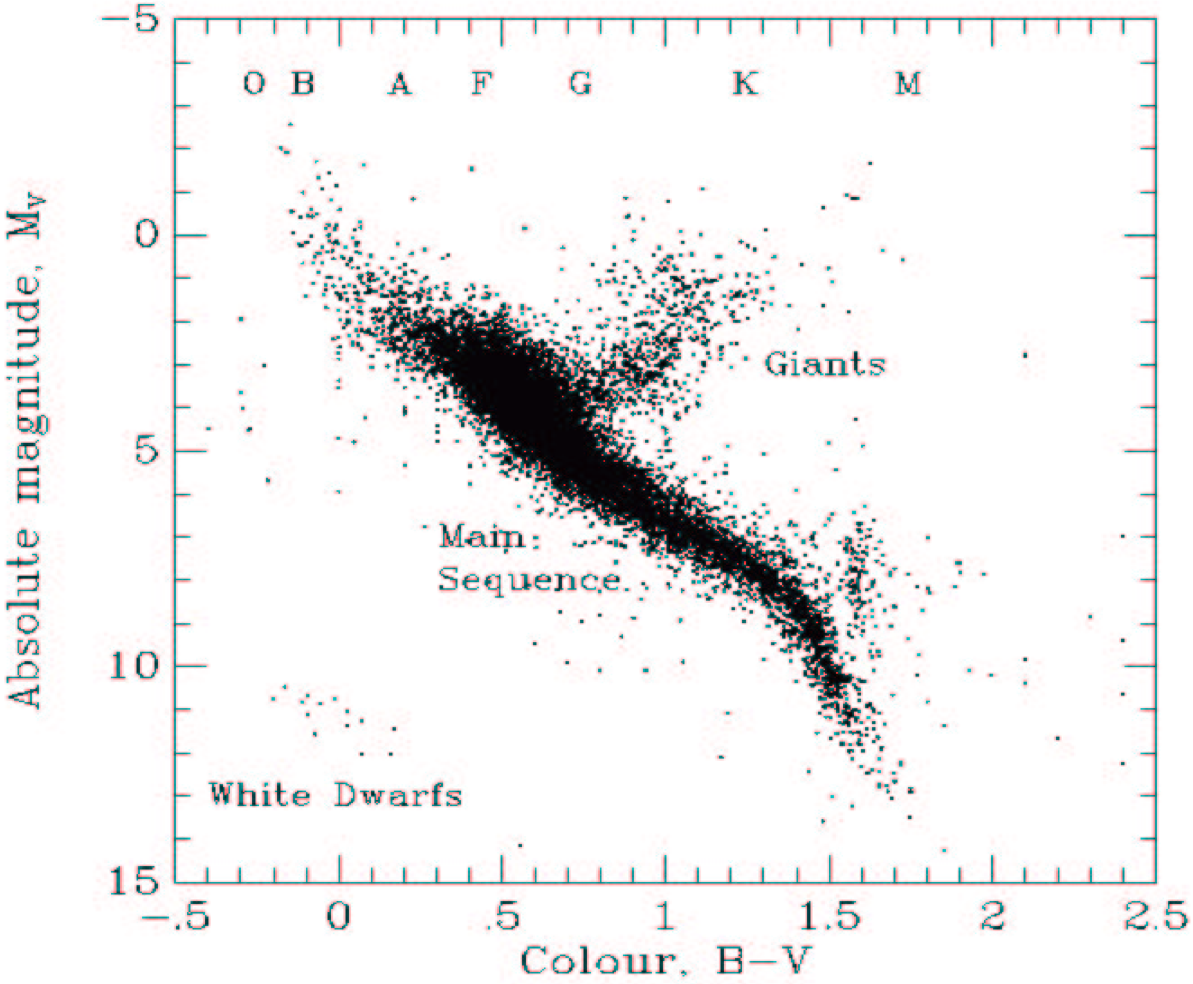
Until the late 1980's only a few hundred stars had been measured accurately in this way, since the effect is very small and difficult to measure with ground based telescopes. The European Space Agency's Hipparcos mission revolutionised this field, measuring the parallaxes of some 120,000 stars, some 15,000 with an accuracy of better than 10%. Distances, D, allow the **absolute magnitude** M_V of the stars to be determined using the **apparent magnitude** V

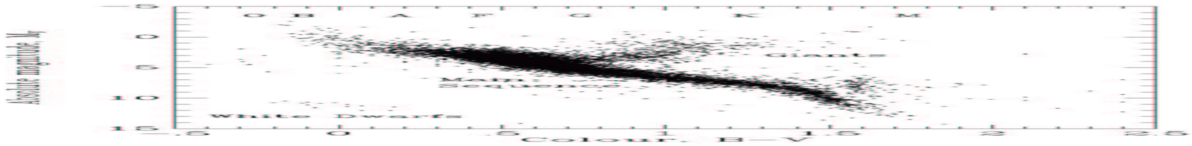
$M_V = V - 5 \log (D) + 5$

The **apparent magnitude** is a measure of the flux from the star as seen at the Earth in a particular pass-band (or filter). The simplest such system for optical light measures the flux in five filters termed U, B, V, R, I for ultra-violet, blue, visual, red and infra-red. The **colour index** of a star is defined by the logarithmic ratio of the flux in two filters

$B - V = 2.5 \log(\text{Flux in B}/\text{Flux in V})$

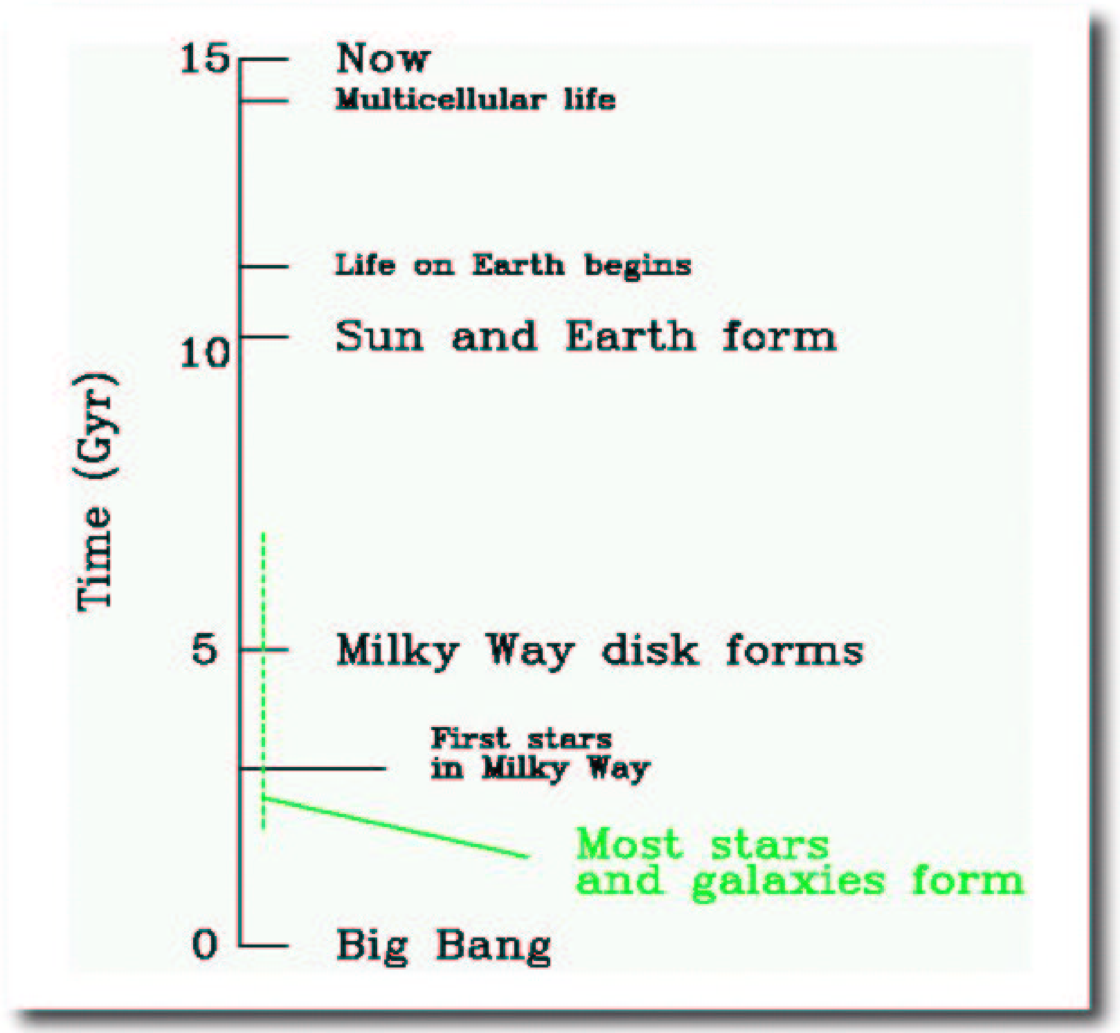
This leads to the **Colour-Magnitude Diagram** (or **CMD**) in which the colour of stars is plotted against their absolute magnitudes. The CMD
of the Hipparcos stars for which the distances were measured to better than 15 % is shown below:

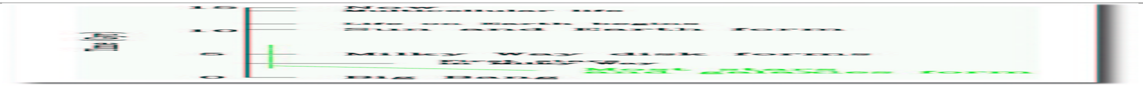


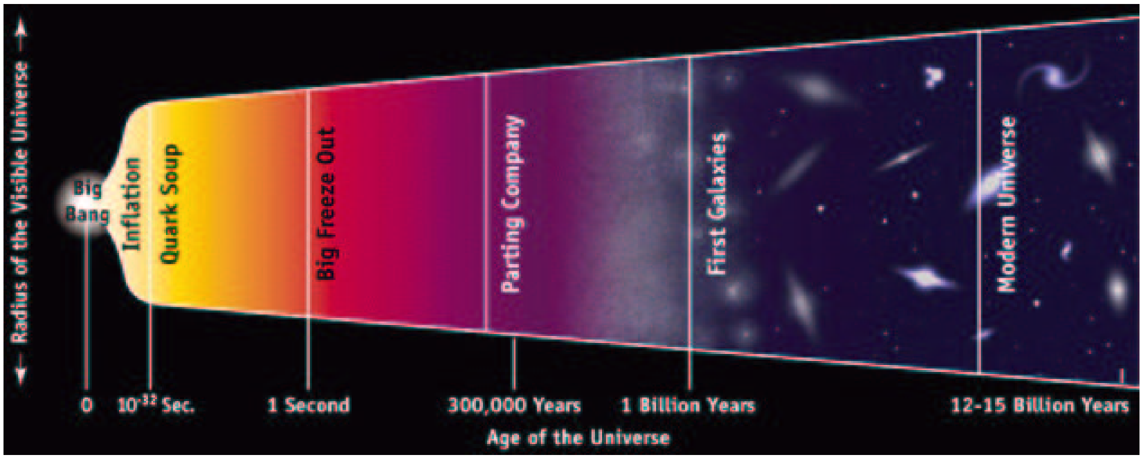


The spectral types are (very roughly) indicated at the top of the diagram. The broad sweep of stars from upper-left to lower-right is called the **main sequence,** and is the site of Hydrogen burning. After stars on the main sequence exhaust their fuel they move off the main sequence and become **giants** (most of the giants seen in the diagram would have been A-G main sequence stars up until a few million years ago), later ending up in the stellar graveyard as **white dwarfs**.

TIMELINE







Quick guide to Gnuplot

In the course you'll need to do some plotting of functions. One way to do this is with GNUPLOT...

Start gnuplot by clicking on the icon or typing gnuplot.

plot out a function	gnuplot> plot sin(x)
plot with some parameters set	gnuplot> plot f(x) = sin(x*a), a = .2, f(x), a = .4, f(x)
plot with x and y axis limits	gnuplot> plot [t=1:10] [-pi:pi*2] tan(t)
set range of X-axis	gnuplot> set xrange [1:10]
set range of Y-axis	gnuplot> set yrange [-pi:pi]
plot out a parabola	gnuplot> set xrange[-10:10] gnuplot> f(x) = x**2 gnuplot> plot f(x)
plot data from a file	gnuplot> plot 'fig5.dat'
define a 2-D function	gnuplot> f(x,y) = x**2+y**2
plot a 2-D function	gnuplot> splot f(x,y)
same with ranges set	gnuplot> splot [x=-5:5] [y=-5:5] [0:200] f(x,y)
define X-axis label	gnuplot> set xlabel "radius [r/R]"
define Y-axis label	gnuplot> set xlabel "temperature [T/Tc]"
read commands from a file	gnuplot> load "linear.gp"
plot several functions	gnuplot> plot p(x),t(x),m(x)

Example input file

t(x) = 1.0 + x - (19.0/5.0)*x**2 + (9.0/5.0)*x**3

p(x) = 1.0 - (24.0/5.0)*x**2 + (28.0/5.0)*x**3 - (9.0/5.0)*x**4

m(x) = 4.0*x**3 - 3.0*x**4

Here are some links to the files you need for the windows version of gnuplot:

GNUPlot zip file

GNUPlot help
