Lecture 1 : From the Big Bang to Stars

1.1 THE BIG BANG

There is persuasive evidence that the Universe was created in "the Big Bang", in which space and time were created in a simple hot energetic, state, about 15 billion ($15x10^9$) years ago.

1.1.1 Five steps from the Big Bang to Stars

• 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).

• 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.

• 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.

• 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.

• 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. A 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.

These steps are illustrated schematically in figure 1.1.

1.1.2 Structure formation — stars and galaxies are born

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 (see figure 1.2) on scales of greater than about 7 degrees.

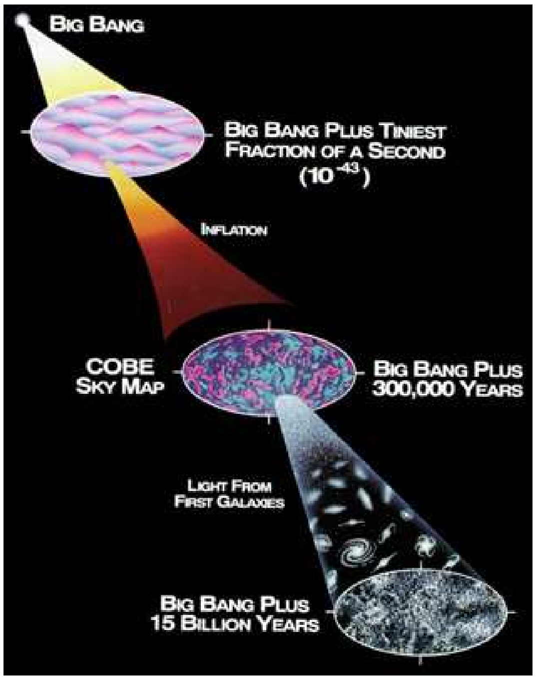

Figure 1.1. Schematic illustration of the steps leading from the Big Bang to the present-day Universe. Light from the first stars re-illuminated the Universe some 1-5 Gyr after the Big Bang. Source: Encyclopedia of Applied Physics, Vol. 23

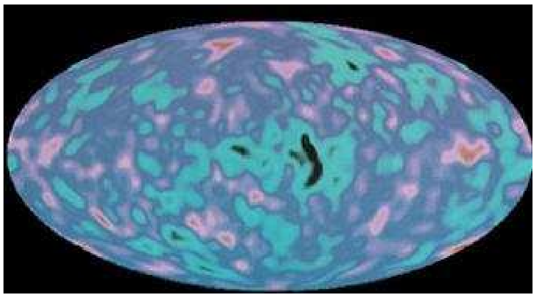

Figure 1.2. Map of the entire sky at a resolution of about 7 degrees, showing vary small variations in the background microwave radiation. These small variations indicate lesser and greater density regions in the early Universe, which would have led via gravity to the structures we see today. Source: Encyclopedia of Applied Physics, Vol. 23 (Page 47 - 81), 1998 WILEY-VCH Verlag GmbH, ISBN: 3-527-29476-7.

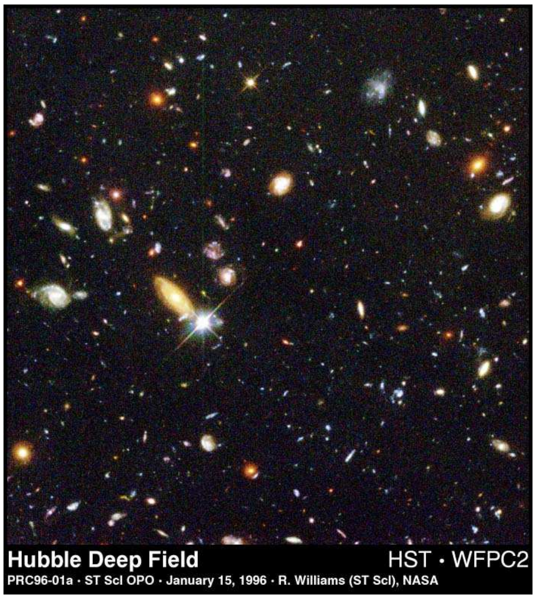

Figure 1.3. Part of the *Hubble Deep Field*, the deepest image of the sky ever taken. The image contains thousands of galaxies and a handful of stars. Some of the galaxies in the image are so distant that the light has taken more than 10 billion years to reach us.

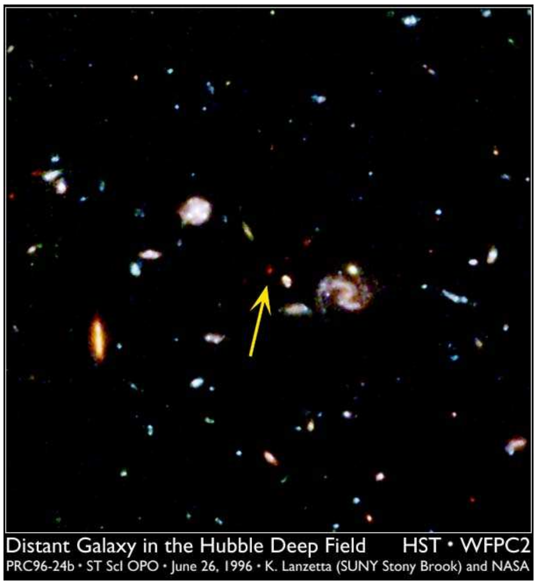

Figure 1.4. One of the most distant galaxies known appears as little more than a coloured spot on this section of the *Hubble Deep Field*. Such distant, high red-shift galaxies give interesting information about how fast the Universe changed from an almost uniform state to the clumpy galaxy distribution we see today, and also allow its minimum age to be determined.

After recombination, the Universe entered a period called the "Dark Ages", until gravitational attraction had operated on very slight over-densities in the matter distribution, leading to the formation of light emitting stars and galaxies. 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 (figure 1.3).

Galaxies have been identified in this image with redshifts which indicate that the light reaching us has been traveling for about 90 % of the age of the Universe — or about 12-15 billion years. One such galaxy is shown in figure 1.4. Such galaxies (and the stars in them) are likely part of the very first generation of stars and galaxies to have 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.

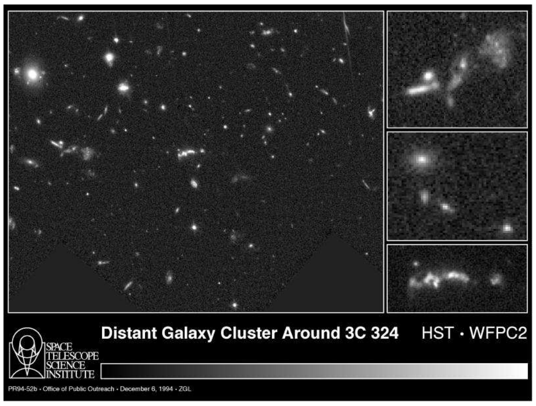

Figure 1.5. Snapshot of very distant galaxies apparently in the early stages of formation. The galaxies have not yet settled into mostly regular forms we see in nearby galaxies, but are very irregular in morphology.

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. Figure 1.5 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.

The space telescope has recently allowed the construction of a sequence of typical galaxy images over time (see figure 1.6). The general picture is that galaxies have been forming over quite a few billion years, are continuing to for-

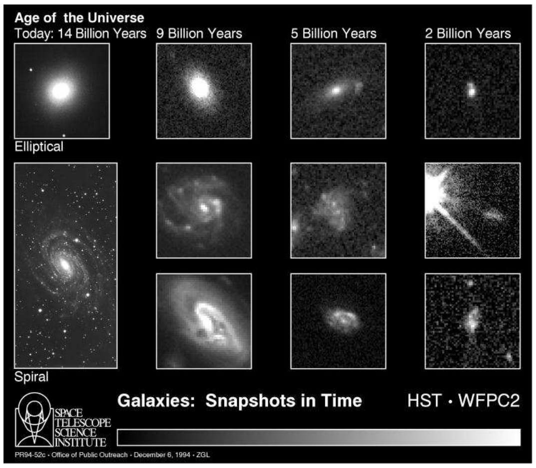

Figure 1.6. Sequence of images of galaxies over the last 12 billion years. For the last 5 billion years or so, almost all galaxies can be classified neatly into two types - spiral and elliptical. In the early times, the "irregular galaxies" (only rarely seen today) become dominant, indicating that the galaxies are still forming.

m and develop still, and seem to have been assembled from many smaller sub-galaxies.

1.1.3 Star formation

In the 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.

Figure 1.7 shows 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 from 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. Figure 1.8 shows how different images in optical (on the left)

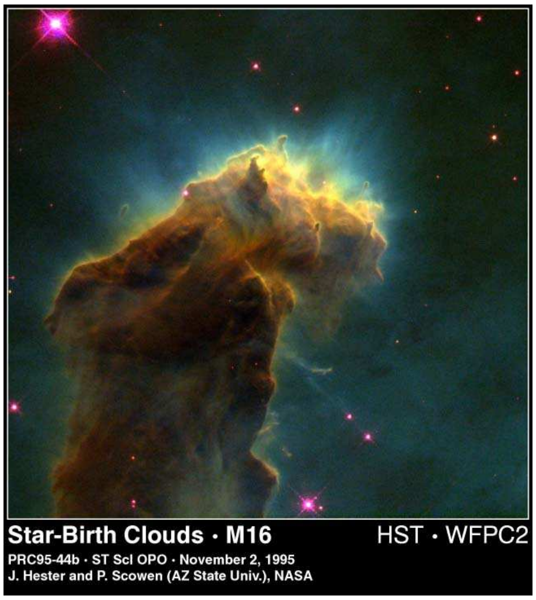

Figure 1.7. Part of the M16 nebula, showing gas and dust clumps cocooning new born stars. The stars will take several million years to emerge from their incubation sites

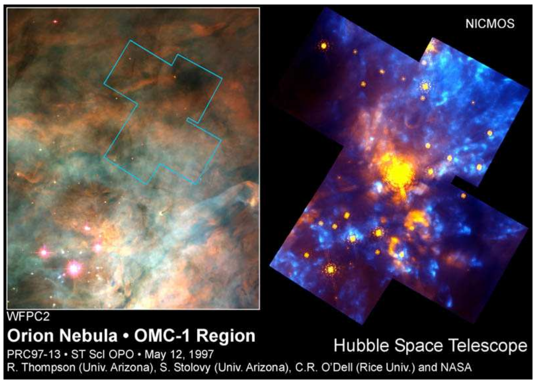

Figure 1.8. Optical (left) and infrared (IR) image (right) of a region of the Orion nebula, taken with the Space Telescope. In the infrared, stars are seen which are quite invisible in the optical. IR radiation can penetrate the clouds of dust surrounding the young stars which are forming in Orion

and infrared (on the right) of the same region in the Orion Nebula can be.

The star forming regions can be very large, sometimes occupying a major section of an entire galaxy, such as seen in figure 1.9.

Out of these star forming regions star eventually emerge — often "en mass" in giant clusters of up to a million stars at once. An example of this is seen in the giant star forming complex 30Dor in the Large Magellanic Cloud, a galaxy nearby to our own (see figure 1.10).

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 earliest times when our galaxy was forming.

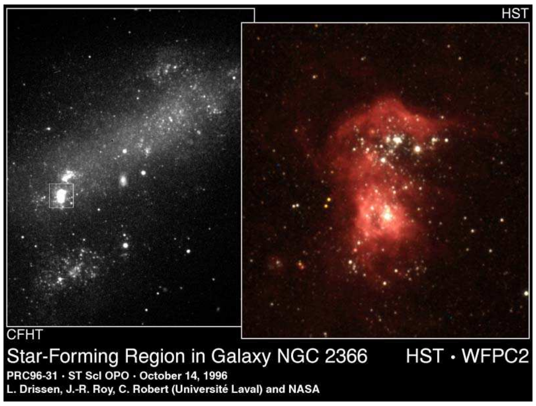

Figure 1.9. Star forming region in the galaxy NGC2363. The region occupies a major fraction of the entire galaxy, showing that the processes by which galaxies develop need not be smooth and regular. Interaction between galaxies is one cause of major star formation events like this

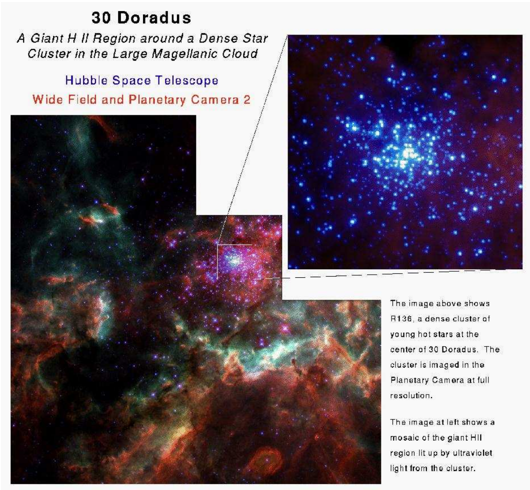

Figure 1.10. A cluster of several thousand new-born stars has recently emerged from a star forming gas cloud in 30 Dor in the Large Magellanic Cloud.

1.1.4 Timeline

A timeline of the processes of gravitational collapse in the Universe, the formation of galaxies and stars, and the formation of our own Galaxy (the Milky Way), Sun and Earth is shown in figure 1.11.

REFERENCES

Hawking's Universe
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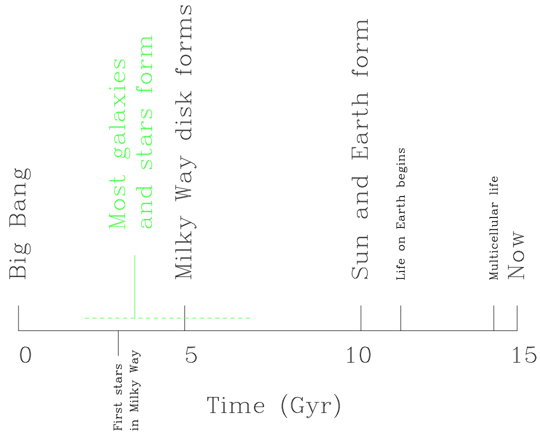

Figure 1.11. Timeline of major events since the Big Bang