Crafoord days

19-21 Sept 2005

Programme—Abstracts—The Crafoord lectures

The *Crafoord* Prize

in Astronomy 2005

CONTENT

CRAFOORD SYMPOSIUM

LUND

From Galaxies to Large-Scale Structures

19 September 2005 at Lund Observatory, Lundmarksalen

10.00	WELCOME. PRACTICAL INFORMATION.
10.10	OPENING AND INTRODUCTION *Gunnar Öquist, Permanent Secretary,* *the Royal Swedish Academy of Sciences*
10.20	THE ROLE OF THE SLOAN DIGITAL SKY SURVEY AND FUTURE LARGE OPTICAL SURVEYS IN COSMOLOGY *James E. Gunn, Crafoord Laureate 2005*
11.05	ANOMALIES IN THE STANDARD PICTURE FOR GALAXY FORMATION AND A POSSIBLE REMEDY *P. James E. Peebles, Crafoord Laureate 2005*
11.50	EXTREMELY LARGE TELESCOPES—WHY AND HOW *Torben Andersen, Lund University, Sweden*
12.10	PRESS CONFERENCE, POSTER PRESENTATIONS, DEMONSTRATIONS
12.40	BUFFET LUNCH
13.25	THE DARK AGE *Sir Martin J. Rees, Crafoord Laureate 2005*
14.10	EVOLUTION OF GALAXIES AND EXTREMELY LARGE TELESCOPES *Arne Ardeberg, Lund Observatory, Sweden*
14.30	NEAR FIELD COSMOLOGY—THE MILKY WAY AND GALAXY FORMATION *Sofia Feltzing, Lund Observatory, Sweden*
14.50	COFFEE BREAK
15.20	THE GALAXY FORMATION—LARGE-SCALE STRUCTURE CONNECTION *Carlos Frenk, University of Durham, UK*
15.55	EARLY BLACK HOLE FORMATION *Melvyn B. Davies, Lund Observatory, Sweden*
16.15	END OF SYMPOSIUM

Welcome!

CRAFOORD SYMPOSIUM

STOCKHOLM

The Structure of the Universe and the Future of Cosmology

20-21 September 2005 at the Royal Swedish Academy of Sciences

20 September

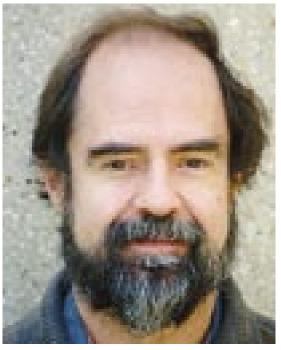
09.00	OPENING OF THE SYMPOSIUM *Gunnar Öquist, Permanent Secretary, the Royal Swedish Academy of Sciences*
09.10	THE ROLE OF THE SLOAN DIGITAL SKY SURVEY AND FUTURE LARGE OPTICAL SURVEYS IN COSMOLOGY *James E. Gunn, Crafoord Laureate 2005*
09.55	RELATION BETWEEN THE CMBR AND LARGE-SCALE STRUCTURE *Licia Verde, University of Pennsylvania, USA*
10.40	COFFEE BREAK
11.10	WEAK GRAVITATIONAL LENSING AND DARK MATTER *Henk Hoekstra, University of Victoria, Canada*
11.55	THE GALAXY FORMATION—LARGE-SCALE STRUCTURE CONNECTION *Carlos Frenk, University of Durham, UK*
12.40	LUNCH
14.00	THE EVOLUTION OF THE GALAXY POPULATION—FROM HIGH REDSHIFTS UNTIL TODAY *Hans-Walter Rix, Max-Planck-Institute, Germany*
14.45	THE INTERGALACTIC MEDIUM AS A PROBE OF GALAXY FORMATION AND COSMOLOGY *Martin Haehnelt, University of Cambridge, UK*
15.30	COFFEE BREAK
16.00	THE STAR FORMATION HISTORY OF THE UNIVERSE *David Elbaz, CEA Saclay / Service d'Astrophysique, France*
16.45	GALAXIES AND QUASARS AT THE HIGHEST REDSHIFTS *Richard McMahon, University of Cambridge, UK*
17.30–18.15	DARK MATTER IN THE UNIVERSE *Katherine Freese, University of Michigan, USA*

21 September

09.00	THE DARK AGE—COSMOLOGICAL CHALLENGES AND PROSPECTS *Sir Martin J. Rees, Crafoord Laureate 2005*
09.45	THE FORMATION OF THE FIRST STARS *Tom Abel, Stanford University, USA*
10.30	COFFEE BREAK
11.00	THE COSMIC BACKGROUND RADIATION WITH PLANCK *Jean-Loup Puget, Université Paris Sud, France*
11.45	ANOMALIES IN THE STANDARD PICTURE FOR GALAXY FORMATION AND A POSSIBLE REMEDY *P. James E. Peebles, Crafoord Laureate 2005*
12.30	END OF SYMPOSIUM

Welcome!

CRAFOORD LAUREATES 2005



James E. Gunn,

born 1938, 66 years old (US citizen), PhD from California Institute of Technology 1966. Eugene Higgins Professor of Astronomy, Princeton University, New Jersey, USA.

P. James E. Peebles,

born 1935, 69 years old (US citizen), PhD 1962 at Princeton University. Albert Einstein Professor of Science, (Emeritus), Princeton University, New Jersey, USA.

Sir Martin J. Rees,

born 1942, 62 years old, (UK citizen). PhD in 1967 at Cambridge University, Professor of Cosmology and Astrophysics at the University of Cambridge, England.

INTRODUCTION

Formation of the Structure of the Universe

A short introduction to the 2005 Crafoord Prize
by Claes Fransson, Stockholm Observatory, Sweden

The Universe shows a wealth of structure on all scales from planets, stars and galaxies up to clusters of galaxies and super-clusters. The origin of this cosmic structure, from galaxies and upwards, is the subject of the work of *James Gunn*, *James Peebles* and *Sir Martin Rees*.

Modern technique has allowed a detailed mapping of the galaxies in the Universe, which has shown that these are not evenly distributed, but are mainly found in clusters and enormous filaments, often referred to as the 'cosmic web' (Figure 1). The origin and history of this structure, and its building blocks, has long been one of the most important problems for astronomy and cosmology.

The first traces of structure in the Universe can be seen in the fluctuations of the cosmic microwave background radiation released about 380,000 years after Big Bang. The origin of the fluctuations can, however, be traced back to epochs much earlier in the history of the Universe, when small quantum fluctuations gave rise to the first seeds. Currently, this is believed to have occurred at an unbelievably early stage of 10^{-35} s!

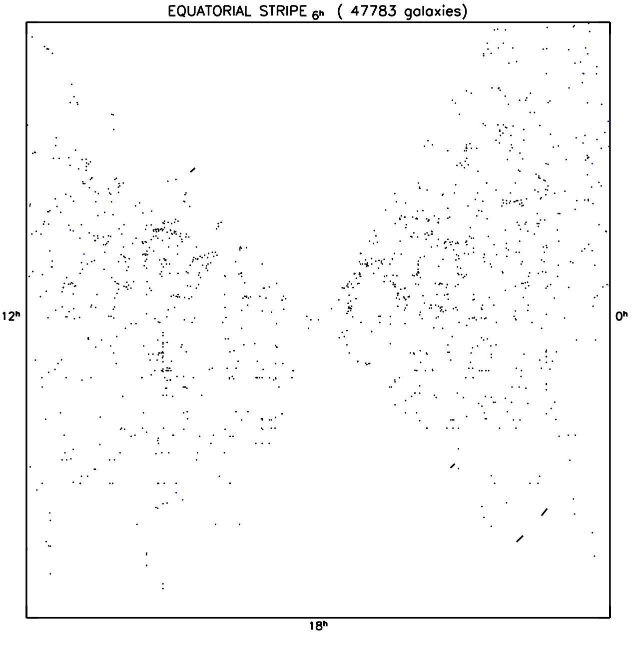


Fig. 1. *Two dimensional distribution of galaxies from the Sloan Digital Sky Survey. Each little dot represents a galaxy. The plot corresponds to a thin slice in the 'vertical' direction, but covering most of the sky in the other direction. The Milky Way is at the centre and the most distant galaxies at the edge of the plot are at a distance of two billion light years. The missing wedges in the centre are caused by the obscuration of the Milky Way. Nearly all galaxies are found in clusters or fi laments, surrounding largely empty bubbles.*

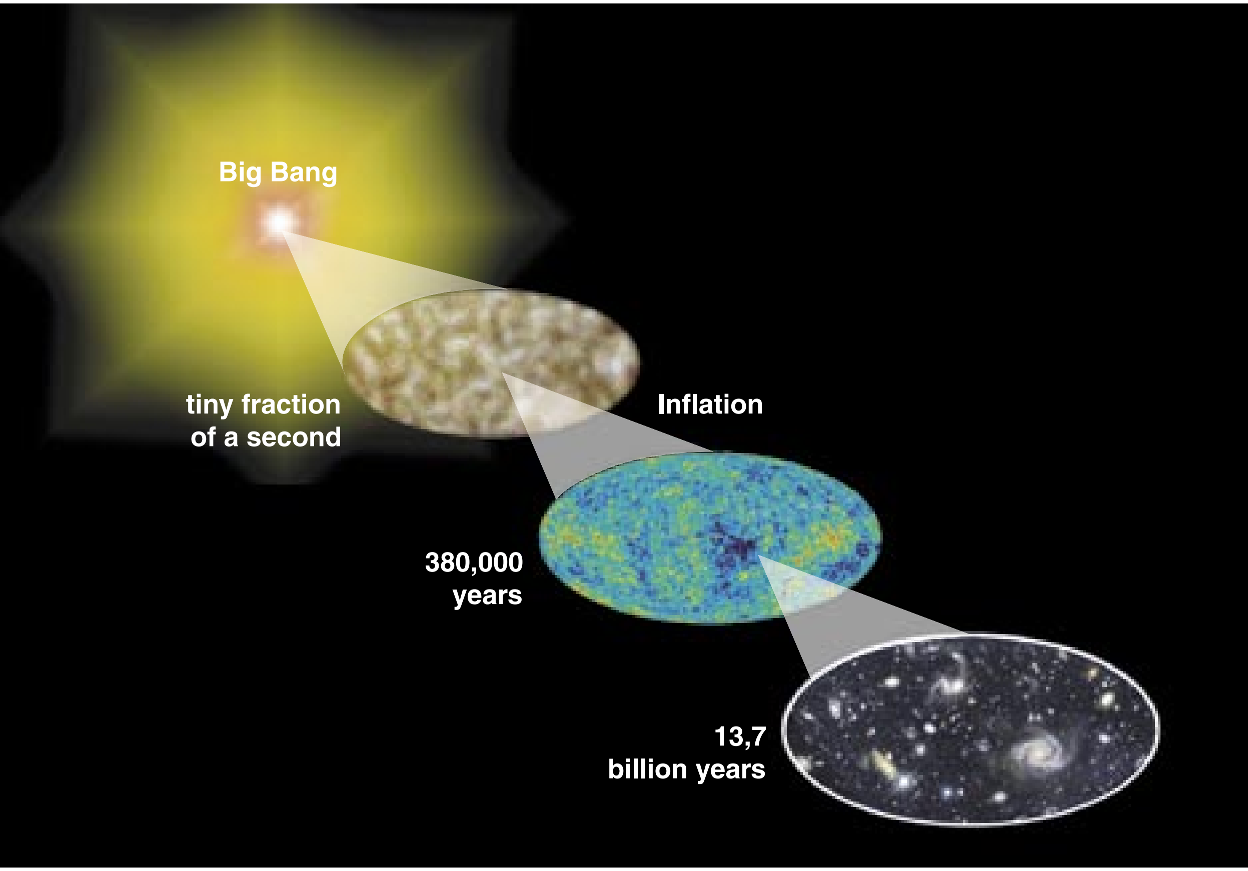


Fig. 2. *The development of structure from the first quantum fluctuations during the first fraction of a second, to the fluctuations in the cosmic microwave background at 380,000 years, and finally to the present. Universe (Illustration: Typoform after NASA/WMAP Science Team).*

Although extremely small, these fluctuations increased in amplitude at the same rate as the Universe expanded, and by an age of a few hundred million years they were large enough for the first galaxies to form (Figure 2). In the now most popular scenario, small galaxies form first, and from these building blocks larger galaxies subsequently form by mergers. Large galaxies, like the Milky Way, are therefore formed as a result of a gradual build-up of smaller galaxy fragments.

Even today galaxies are forming and merging with each other, albeit at a much lower frequency than in the early Universe. Not only galaxies were formed in this way, but structures of all sizes and masses formed as a result of this hierarchical process.

Although the visible galaxies, consisting of ordinary matter made up of electrons, protons and neutrons, act as the most important tracers of this structure, the dominant ingredient in this galaxy formation scenario cannot be seen directly. Today we know that there is about five times as much “dark matter” as that which is visible. The nature of this dark matter is unknown, and represents one of the main puzzles in physics and astrophysics today. We only know that it interacts extremely weakly with other matter, except for by gravitational attraction. The most popular candidates for dark matter come from the so-called supersymmetric particle physics theories.

The gravitational attraction of this dark matter determines the growth of the gravitational wells, where the normal, visible matter ’falls in’ and forms the structure we see today in the form of galaxies and larger structures. The resulting structure therefore reflects the properties of the dark matter. There is therefore a fascinating connection between physics on the smallest scales to the largest structures we have in the Universe. From comparison of computer simulations of the Universe and the maps of the large-scale structure one finds that most of the structure we see has developed from a gradual hierarchical build-up.

James Gunn,*James Peebles* and *Sir Martin Rees* are together responsible for many of the main ingredients of the current picture of galaxy and structure formation in the Universe.

James Gunn first made theoretical contributions to the field of galaxy formation, the gaseous medium between galaxies and the presence of dark matter in galaxies. Later, he has played a central role in several observational projects, like the Hubble Space Telescope and the Sloan Digital Sky Survey, which aims to chart the properties of one million galaxies.This has become one of the main observational sources of information about the structure of the Universe.

James Peebles predicted some of the most important properties of the fluctuations of the microwave background radiation already around 1970. He later developed the basis for the statistical description of the structure in the Universe. Peebles has been one of the main proponents of the now most popular version of galaxy formation, the Cold Dark Matter theory, with the hierarchical evolution of the structure as its main characteristic.

The work of *Sir Martin Rees* includes understanding the physical processes determining the observed properties of galaxies, such as their typical masses. Early on he recognized the importance of dark matter for the formation and properties of galaxies, which has stimulated extensive computer simulations of the large-scale structure. He has lately developed important ideas in relation to the epoch when the first stars and galaxies formed, and suggested important observational tests of this ‘dark age’ in the history of the Universe.

Cosmology—A Discipline Coming of Age

James E. Gunn, Princeton University, USA

Your Majesties, President of the Academy, members of the Crafoord family, members of the Academy, ladies and gentlemen. It is a great honour to have been awarded the Crafoord Prize.

I began serious work in cosmology in 1964. At that time, and in the decades previous since the discovery of the expansion of the universe by Hubble, Slipher, and Lundmark in the late 1920s, the subject was, to say the very least, severely data-starved. We knew that the universe was expanding, that the linear Hubble expansion law which states that the speed of recession of a distant galaxy is proportional to its distance with a universal constant of proportionality, the Hubble constant, was at least approximately obeyed out to velocities approaching half that of light. We knew that the galaxies in the universe were arrayed about us in a manner which was approximately independent of the direction we looked.

These observational facts, the strong Copernican bias that we should not be in any way special or privileged observers, and a healty dose of wishful thinking, led most workers to conclude that the universe was probably described reasonably well by one of the simple Friedman model universes within the framework of Einstein's general relativity. These models obey a very strong Copernican principle, the Cosmological Principle; all particles participating in the expansion are completely equivalent. They are described completely in their simplest form by two observed quantities: The Hubble constant and the average density of matter in the universe at the present epoch. From these one derives the age of the universe (the time since the Big Bang, a fiery beginning shared by all of these models), the geometry of the universe (is space flat or curved, finite or infinite?), and the far future history of the universe (will it expand forever or stop and collapse upon itself in a Big Crunch?)

One variant on the simple Friedman models was considered, at the time though of as a variant on General Relativity, that there might be term in the Einstein equations called the Cosmological Constant, introduced and later rejected by Einstein. It was taken as seriously as it was mostly to help reconcile the ages derived from the Hubble constant and those derived from geological evidence and the theory of stellar evolution, which suggested at the time that the universe was younger than things in it (!). But most workers realized that the observational uncertainties were so great that such a bold step was premature; it was clearly to be preferred that the universe could be described by the laws of physics we knew *and* that the universe was made of stuff we knew about.

It is worth pondering at length this almost supreme act of hubris, which alone makes the subject of cosmology resemble a science, though in actuality it is, of course, not—lacking as it does the crucial scientific ingredient of repeatable experiment. We have seen in the years since the 1960s that we cannot any longer hold to these fond simplistic hopes, and the shift has been to minimize and simplify that which we do not understand to some bare minimum which at least gives some hope of eventual understanding. It is yet to be seen whether this approach will be successful, though it is hard to see how any other productive course could be taken and leave the scientific facade of cosmology intact.

Two epoch-making discoveries in the middle 1960s launched the subject on the road it has followed since. The first and most important was the discovery of the Cosmic Microwave Background (CMB), the microwave radiation which fills all of space and is certainly the relic of a very hot early universe less than a million years after the Big Bang. It is astonishingly uniform over the sky, constant to about a part in 100,000, though the tiny bumps and wiggles in it at this level are certainly the seeds from which all structure we see in the universe today is formed.

The second was the discovery of quasars, objects now believed to be associated with the infall of matter into very massive black holes in the centers of galaxies, and very much brighter than their parent galaxies. These objects can be seen to enormous distances and hence have very great recession velocities, up to more than ninety-five percent of the velocity of light, and we see the most distant of them as they were when the universe was only a few percent of its present age. It soon became clear that there were very many more of these objects in the universe at very early times than at present, and so for the first time astronomers could see evolution directly.

These discoveries made cosmologists take very seriously the simple Friedman models, since the evidence was now very strong that we lived in a universe which was very accurately so described and which began in a Big Bang.

In the midst of this work in the last decades of the last century it became clear than one of cosmology's cherished tenets—that the universe was made of stuff we understood—had to be abandoned. Most of the matter in the universe is 'dark matter', stuff which gravitates but does not, evidently, interact with ordinary matter or itself any other way. Since its interactions are simple, its existence has hardly derailed the progress of cosmology, and it was/is simply regarded as another constituent, though its existence should have sounded a cautionary note. More recently an even more startling development has occurred—most of the *energy* in the universe is evidently not in the rest mass energy of ordinary or dark matter, but is instead in a mysterious "dark energy" which behaves, as far as we can tell today, exactly like the cosmological constant which Einstein discarded. Thus even as we became quite sure we lived in a Friedman universe, the makeup and description of that universe has become quite complex.

My own primary work in cosmology has been very much in a peripheral area, namely the one of technological development and support. Neither of the major cosmological discoveries discussed above—the CMB and quasars—were the result of *intellectual* breakthroughs; indeed, both were essentially accidental, enabled by technological advances in microwave radiometers in the one case and very low light level imaging detectors in the other. Photographic plates were the imaging medium of choice (there was no other) in astronomy for decades, though they suffered from many serious problems. Among these were extreme inefficiency—a light signal from a distant object in the universe carries with it a certain finite information content in the photons which make up the signal, and photographic plates capture substantially less than one percent of that information. In addition, retrieving quantitative information from plates is very difficult because their response is very complex and nonuniform. In the 1960s and 1970s great strides were made in detector technology, first with photoelectric devices and then with native silicon detectors, culminating with the development of charge-coupled-device (CCD) detectors in the 1970s. CCDs are nearly ideal detectors; throughout most of the visible spectrum, their efficiency is about seventy percent, more than a hundred times that of photographic plates, and the electrical signal is very precisely proportional to the light signal. We applied CCD detectors to astronomy at the Hale telescope at Palomar, pushing the redshift limit of galaxies to one, at which epoch the universe was half its present size, and for quasars to 4.9, at which epoch the universe was about one-sixth its present size and a tenth its present age. The distant quasar search was done in a scanning mode in which data are gathered continuously, making use of a mode of operation unique to CCD detectors. Still, large surveys in astronomy could only be done with photographic plates, because CCDs were simply not large enough to image very much sky at once.

In the 1990s, finally, integrated-circuit technology became mature enough to allow the fabrication of large imagers, and we began planning a project to image more than a quarter of the sky using the scanning mode with a new dedicated telescope equipped with a large multi-CCD camera and to use CCDS and the developing technology of fiber optics to obtain redshifts and hence distances for a million galaxies and a hundred thousand quasars. This project was to become the Sloan Digital Sky Survey (SDSS), whose spectacular success is certainly the primary reason I am speaking to you today. I would stress, though, that I am merely its originator and designer, and, today, a spokesperson for it; it would not have happened without the efforts of hundreds of others at the many institutions involved in the project. It is one of the sources of data which has transformed cosmology from a data-starved subject a few decades ago quite unable to determine the two numbers workers thought provided a complete description to one in which a flood of new observations and data keep a thriving community of theorists busy, and from which a quite precise model of a complex universe has emerged—cosmology has indeed come of age, and most of the parameters which affect the directly observable aspects of the universe and the structure in it are known to of order ten percent or, in many cases, much better. None of this could have come to pass without the startling technological developments of the past few decades.

The SDSS was conceived primarily as a cosmological survey, aimed at deriving cosmological parameters from the statistics of the distribution of galaxies in space, though its accomplishments have been much broader. We have discovered many tens of quasars more distant than the most distant known at the outset of the survey. A few of these are far enough away (and hence early enough) that they shine to us from an era before the first stars and quasars had reionized the universe and rendered it transparent again to the ultraviolet light which we see as optical light today because of the redshift. We see them only in the farthest infrared part of the spectrum covered by CCD detectors, and we know that the discovery of more distant objects will have to be done in the farther infrared, which will require yet another technological revolution.

We see the signature of sound waves in the early universe in the statistical structure of the tiny fluctuations in the CMB, and the SDSS not only sees the expected gross statistical properties of the distribution of matter in the universe as mirrored in galaxies that we expect to evolve from what we see in the CMB, but in addition see the vestiges of the sound-wave signature. This allows us to tie the geometric properties of relatively recent universe accurately to those at the time the CMB was formed when the universe was less than a million years old. Combining the statistics of the galaxy distribution with the distribution of clouds of gas inferred from the light of distant quasars shining through those clouds on its way to earth constrains the physics of the early universe in ways which will eventually help us to understand why the universe is so uniform today. The SDSS data, together with data from the CMB and from other optical surveys, converges on a model for the universe called the "concordance model", one in which about seventy percent of the energy density in the present universe is in dark energy, four percent in ordinary matter made of electrons, protons, and neutrons, the rest in dark matter. The universe is thirteen billion years old, space is flat and the expansion is currently accelerating under the influence of the dark energy, which with existing data is consistent with an unchanging cosmological constant.

In our own Milky Way galaxy, the survey has uncovered streams of very old stars from smaller galaxies which have been consumed by our own after ancient collisions. The existence of these lend credence to the notion that galaxy formation is a messy process of agglomeration of smaller systems, and when the survey is finished we hope to be able to make quantitative statements about the importance of these processes in the formation of the Milky Way.

Closer to home, we have discovered a large population of brown dwarf stars, objects intermediate in mass between ordinary stars and planets, and even closer thousands of asteroids in the solar system whose properties can be much more accurately inferred from the very accurate SDSS data than from earlier surveys. The chemical properties deduced from their colors and the close ties these have with the various orbit families they belong to promise to elucidate the chemical history of the early solar system and tell us something about its formation.

These examples make it clear that the survey has made itself felt across almost all of astrophysics, but its greatest contribution may in the end not be the science obtained from it but instead simply the demonstration that doing astronomy this way, obtaining large amounts of accurate, widely useful, data in a very uniform, well-controlled and well-understood way works and is very effective. Cosmology especially, but indeed most of astrophysics is inherently a statistical subject dealing with the properties of large populations of objects. Nature performs the experiments; we merely observe the outcomes, usually for a tiny snapshot in time. These observations must be pieced together much as an archaeologist pieces together shards of an ancient pot, and there is no substitute for large quantities of very well-understood data to make this process a success.

Physical Cosmology

P. James E. Peebles, Princeton University, USA

Your Majesties, President of the Academy, members of the Crafoord family, friends and colleagues, ladies and gentlemen, I am deeply honored to receive the Crafoord Prize jointly with James Gunn and Martin Rees for contributions towards understanding the large-scale structure of the universe: the exploration of the nature of the universe on the largest observable scales and of the laws of physics that govern its nature.

Research in this branch of science, physical cosmology, has had the character of "a dog's walking on his hinder legs. It was not done well, but you were surprised to find it done at all."[1] The usual kind of experiment is impossible in cosmology. We cannot visit another galaxy, and push on it to see how it responds, we can only collect observations of the radiation the galaxy happens to send our way, collect other such scraps of information, and hope to piece them together into a useful empirical basis for our ideas about what the world is like on large scales. As might be expected, the enterprise has left pronounced gaps in our understanding. The surprise is that we have obtained a well-checked empirical basis that establishes a considerable variety of aspects of the large-scale nature of the universe.

When I began working on this subject four decades ago it had an empirical basis, but a narrow one that was heavily overburdened by theory. The imbalance made me uneasy. I could see a few interesting things to do, after which I expected I would move on. That never happened because each project suggested others that kept me occupied and happily wondering how it might all work out. It certainly helped that not many people were active in cosmology then: as a junior scientist I could work on fertile but little explored ground, by myself or with a few graduate students, with little need to think about competition in a small community of scientists, most of whom I got to know. The community is so large now that I need young colleagues to guide me to the people and the literature, but I certainly don't miss the old days. Now there are broad observational programs—an elegant example is the one led by my colleague Jim Gunn—that have produced a rich fund of data that tie together into a convincingly checked theory of how our universe expanded and cooled and grew its galaxies of stars.

The history of how we arrived at this cosmology fills books. I can only describe a few examples of what has been learned, list some of the problems we have left for the next generation, and name as particularly important to me a few of the people who have contributed to our present state of understanding.

We have established that the observ-

[1] This is adapted from a quite unfair remark by Doctor Samuel Johnson quoted by James Boswell in his diary of 1763.

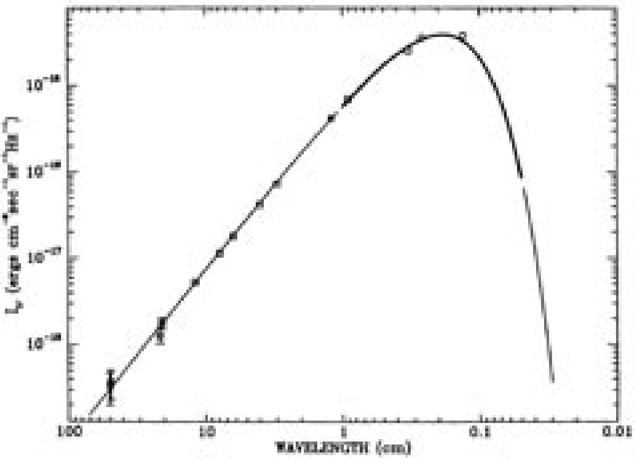


Fig. 1. *The thermal radiation that fills space, a fossil left from the early stages of expansion of the universe. This figure was made by David Wilkinson.*

able universe is close to homogeneous in the average over large scales—it has no center and no edge we can see—and it is expanding from an earlier much denser and hotter state. This is sometimes called the Big Bang cosmology, but I avoid the term because it's misleading: the theory is not about an event that might be compared to an explosion but rather about how the universe has evolved. Robert H. Dicke, my teacher when I was a graduate student at Princeton University and my professor of continuing education, led us to a key piece of the evidence for this evolution: space is filled with radiation with a thermal spectrum—the blackbody radiation you feel when you hold your hands before a hot fire—that is a fossil remnant from a time when the universe was young and dense and hot. Figure 1 shows the evidence. The thick line is a measurement, by two groups. David Wilkinson, a friend and colleague since we both started working on this subject, was a key figure in the measurement from a USA NASA satellite. Herb Gush, at the University of British Columbia in Canada, led an independent measurement, from a rocket flight. The symbols show other measurements made at discrete wavelengths. The thick line is so smooth it looks like a theory, but it is a measurement over a smooth range of wavelengths. The theory, shown as the thin line, has one parameter: the measured temperature is T = 2.725 K. Theory and experiment are close, as required of a fossil from a time when our universe was very different: dense and hot enough to have been able to relax to thermal equilibrium. Many contributed to this beautiful result; Bob Dicke played the central role.

The universe is clumpy on smaller scales: stars appear in the concentrations we call galaxies and the galaxies appear in the clustering pattern illustrated in Figure 2. These data were taken by another of my heros, Donald Shane, at the Lick Observatory in California. He and his assistant Carl Wirtanen counted the brightest one million galaxies, by eye with a traveling microscope; it occupied much of their time for ten years. There was not much you could do with a million numbers before high speed computers, but they took the data with such care that two decades later we could turn it into statistical measures of the clustering pattern, and make a map, a 50 by 90 portion of which is shown here. I had the pleasure of showing the map to Donald and asking him if this is what he was seeing. He laughed and said "I was looking at this one galaxy at a time."

Statistical measures from this and newer surveys show that the galaxies are distributed in an elegant hierarchical clustering pattern—clumps within clumps—of the kind Benoit Mandelbrot termed a scale-invariant fractal. (The small-scale galaxy distribution has fractal dimension D = 1.23.) This pattern extends to scales of about one percent of the distance light has travelled since the universe was young. On larger scales the distribution is close to homogeneous. On the small-scale side the pattern ends at the galaxies; they might be termed the peaks of the clustering hierarchy. These results suggested to us that galaxies and their clustering grew by the pull of gravity on small departures from exact homogeneity present in the very

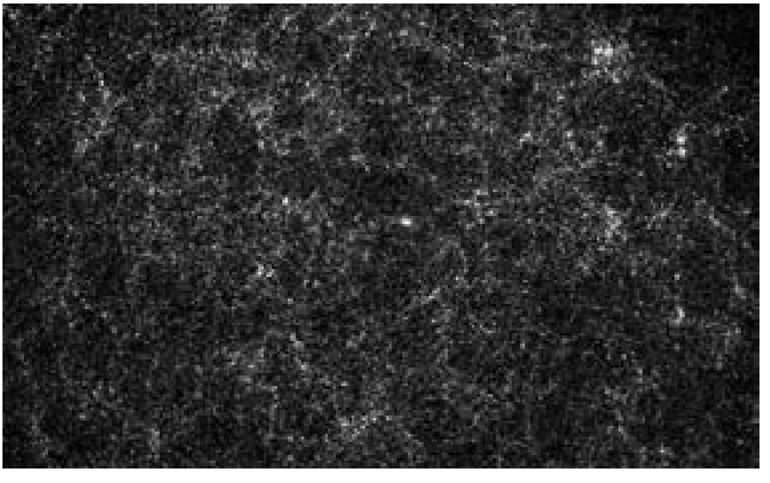


Fig. 2. *The distribution of the nearby Shane galaxies, in a patch of the sky centered on the North pole of our galaxy.*

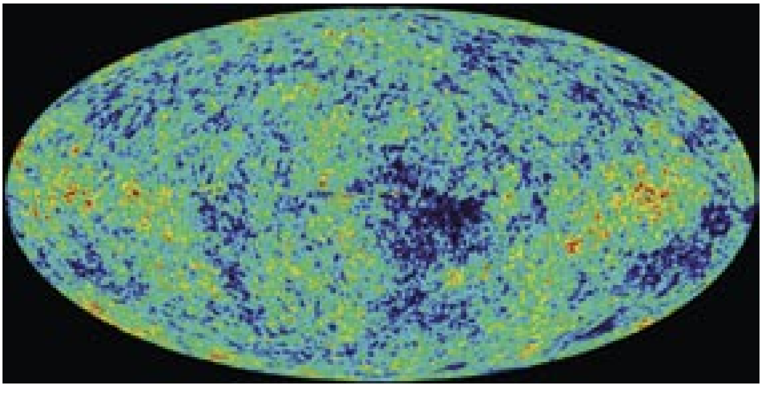


Fig. 3. *The WMAP sky. The hottest and coldest spots differ in temperature by about one part in 10,000.*

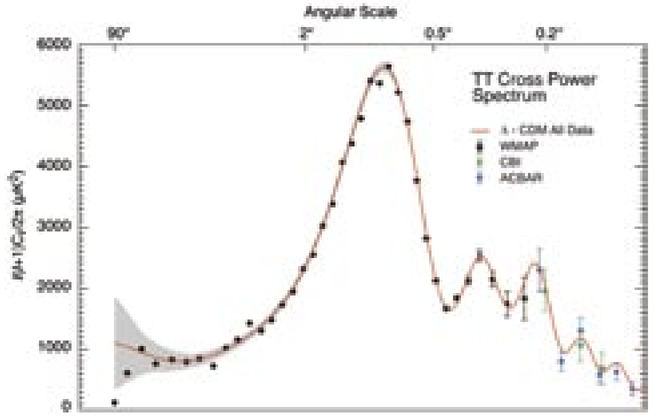


Fig. 4. *A measure of the mean square fluctuations in the temperature of the fossil radiation across the sky, from theWMAP science group.*

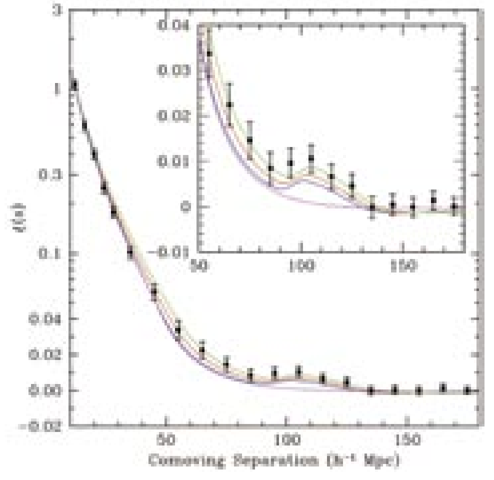


Fig. 5. *The spatial correlation function of luminous red galaxies obtained by Daniel Eisenstein and colleagues.*

early universe. We have a test, because gravitational growth of clustering of the matter would disturb the fossil thermal radiation in a way that can be computed and measured. Figure 3 shows that the radiation has been very slightly disturbed from homogeneity. In this map of the whole sky the mean temperature is subtracted, the directions where the temperature is high are shown in red, and low are shown in blue. These data are from the Wilkinson Microwave Anisotropy Probe (WMAP) NASA satellite mission. It is named in honor of David Wilkinson, who contributed so much to the art of these measurements. We were saddened by his death, before completion of WMAP, but comforted somehow that he did see its great success.

To turn these measurements into a test we must replace the images in Figures 2 and 3 with numerical measures that the theory can predict. The measures in Figures 4 and 5 are based on the mean square fluctuations of galaxy counts within cells in space and the mean square fluctuations of the radiation temperature averaged within cells on the sky. (To be a little more technical, Figure 5 is the galaxy position correlation function. The Legendre transform of what is plotted in Figure 4 is the temperature angular autocorrelation function.)

The theory that gives the successful predictions shown as the solid lines in the two figures depends on a series of assumptions, to begin with that the large-scale behavior of the universe is well described by Einstein's general relativity theory. It accepts the idea that the universe expanded from a hot dense state that produced the fossil radiation shown in Figure 1. In the very early stages of expansion this radiation was hot enough to ionize hydrogen, and the free electrons strongly scattered the radiation, as in a dense fog. The energy density of the radiation and its drag on the plasma were large enough at early times to prevent the gravitational growth of clustering of the matter. That changed when the temperature cooled to about 1,000 times its present value, the plasma combined to neutral atoms, and the fog cleared. This decoupling of radiation from the slightly clumpy matter imprinted irregularities on the radiation. These irregularities are observed: they are the temperature fluctuations shown in Figure 3 (apart from some small adjustments for residual interactions at later times). Gravity caused the clustering of the matter to grow from the small fluctuations that existed at the time of decoupling into the very clumpy present-day distribution shown in Figure 2. We worked out this physics not long after the fossil thermal radiation was discovered. But turning it into a prediction requires an understanding of what the universe is made of, which took longer.

We and the planets and stars are made of baryons. It would be natural to suppose that the universe is made of baryons too, but by the early 1980s we knew that the thermal fossil radiation is too smooth to be consistent with a pure baryon universe. I added to the cosmology dark matter—a hypothetical substance of which we know little except that it acts like a gas of nearly free particles—in order to show that the quite smooth fossil radiation is not necessarily inconsistent with the idea that the strong clustering observed in the present distribution of matter grew by gravity out of small beginnings at early times. That consistency requires that most of the mass of the universe is something hypothetical. The model nevertheless was promising and became popular, but I was more interested in the growing evidence that the mass in baryons plus dark matter is too small for a universe that is expanding with escape velocity. That led me and a few others to propose that we restore a second hypothetical component, the cosmological constant . Einstein had introduced—and then rejected it as logically unneeded—a half century earlier. I remember younger colleagues accusing me of being silly. But I was serious, as was the evidence, and subsequent work by the growing number of people in cosmology has by now made the case compelling. As this was happening I was feeling nervous about all these assumptions, and I have to admit that my contrarian instincts made me wonder whether a theory that became so popular so quickly could be trusted. In the late 1980s and the 1990s I explored other sets of assumptions for how structure formed, each no more unreasonable on the face of it than what I have mentioned, but the steadily improving bounds on fluctuations in the fossil radiation ruled out these alternatives as fast as I was producing them. In 2003 the fluctuations were detected in the wonderful detail shown in Figures 3 and 4, and seen to be what would be expected in a universe dominated by the hypothetical and dark matter. The search for alternatives was a useful exercise, for me at least, because the lack of a viable alternative adds to the case that the universe has this curious composition.

The measurements indicate that about 4.5% of the mass of the universe is in baryons, 20% in dark matter, and the rest in. These numbers are based on several constraints, important among them being the fit of the theory to the observations shown in Figures 4 and 5. The wiggles in these figures result from the behavior of baryons and radiation before decoupling: they act as a fluid which the radiation pressure causes to oscillate as a sound wave. The wiggles indicate special wavelengths favored for early growth, in rough analogy to the way waves in the water in a pond have favored wavelengths that fit within the width of the pond. And the values of the favored wavelengths depend on the composition of the universe: the baryons affect the velocity of sound in the early baryon-radiation fluid, and the dark matter affects the rate of expansion of the universe. The favored wavelengths have a prominent effect on the statistics of the radiation distribution in Figure 4. They are present but harder to see in the statistics in Figure 5 for the matter distribution. The bottom curve without the bump at separation 100 Mpc (about 300 million light years) shows what would have happened if the mass in baryons were negligibly small: the baryons are needed to produce the slight but real bump. (When this bump was discovered last year it reminded me that I had predicted it under the conditions of this theory, but could not remember whether I had published the calculation. While writing this essay I managed to find that I had written it up, 25 years ago. I checked that the lead author in in the discovery of the bump, Daniel Eisenstein, did not know about this old work. This is healthy: it's a good thing that the young turks don't feel the heavy hand of the old guard, while knowing that they do have our input when wanted).

You will have noticed that the fit of theory and observation in Figures 4 and 5 depends on quite a few assumptions, many of which were chosen for the purpose of getting the theory and observation to agree. But this is not mere curve fitting: we have a far fewer free parameters than independent checks of consistency, including the way the theory represented by the curves in Figures 4 and 5 so closely follows the measurements as functions of angular separation for the radiation and spatial separation for the galaxies. My conclusion is that the theory almost certainly is a good approximation to reality. I marvel at the result: we have a demanding and successful test of the physics—including general relativity theory—of the structure of the universe on scales of some ten thousand million light years.

When you consider that we are trying to explore exceedingly large issues with the help of relatively little data you may not be surprised that there are open questions. What is the nature of the dark matter? Is it really a gas of free particles, or is that just the simplest approximation we can get away with at the present accuracy of the tests? Einstein's has been given a new name, dark energy, but that makes it no more respectable: it is not at all natural within well tested ideas about fundamental physics. So what are we missing? These are among an impressive set of homework assignments we are leaving for the next generation of cosmologists. But the progress we have made is impressive too.

The starting assumption of physical science is that nature operates by rules we can discover, in successive approximations. Cosmology adds another demonstration of the power of this assumption.

Probing the 'Dark Age' of Cosmic Evolution

Sir Martin J. Rees, Cambridge University, UK

Your Majesties, President of the Academy, members of the Crafoord family, members of the Academy, ladies and gentlemen. It is a great honour to have been awarded the Crafoord prize. I am specially privileged to be sharing it with two friends and colleagues who I have respected and admired since my student days.

It was my good fortune to have started my research career in the mid 1960s. That was a time when two interlinked subjects—cosmology and relativistic astrophysics—were in their pioneering stages and were for the first time acquiring an empirical base. The most important single discovery during those years was, of course, the microwave background radiation. This was quickly interpreted, by Jim Peebles and others, as a relic of the hot dense early phase of cosmic history. Ever since the late 1960s, the 'hot big bang' theory has set the framework for increasingly refined analyses of how our universe evolved from a dense beginning to its present structured state—in particular, how galaxies originated, how they evolve, and how they are distributed through space.

Another important realisation in the 1960s—initially through the efforts of radio astronomers—was that some galaxies are more than just assemblages of gas and normal stars. These 'active galaxies' harbour, in their centres, an exotic and powerful source of energy. This source is still not fully understood, but almost certainly involves black holes as massive as millions (or even billions) of stars. Einstein's general relativity is now recognised to be crucial, not only to the dynamics of our entire universe, but for a proper understanding of the most energetic objects within it. Massive holes lurk in the centres of almost all galaxies—though in most cases, including our own Galactici Centre, the holes are quiescent rather than currently active.

Even though their physics was then deeply mysterious, 'active galactic nuclei' (AGNs) figured prominently in cosmological discussions back in the 1960s. Their emissions were so powerful that they could be detected out to far greater distances (and therefore further back in time) than normal galaxies. Indeed, the first clues that the universe was not in a steady state came from statistical evidence that galaxies had a greater propensity to be 'active' when the universe was 1/3 or 1/2 of its present age than they do today.

Telescopes and detectors are now sensitive enough to survey large populations of normal galaxies not only in our cosmic locality, but out to such immense distances that their light set out when the universe was only a tenth of its present age. AGNs are consequently less important for cosmology than they once were. However, they remain fascinating—and have continued to be a focus of my own research—because they are important for the 'energy budget' of the galaxies and of intergalactic space. Also, they involve intriguing physics.

Indeed, one motive for studying extreme astrophysical phenomena is that one may thereby learn some new basic physics. The cosmos offers a 'laboratory' for probing conditions unachievable on Earth: for example, the ultrahigh temperatures in exploding stars and in the 'big bang' and the strong gravity around black holes. Astrophysicists now have a symbiotic rather than parasitic relation with their physicist colleagues.

But there's one thing that cannot be overemphasised. The marvellous astronomical advances in recent decades owe relatively little to armchair thought. They have stemmed primarily from ever more sophisticated technology: observers now use far more sensitive sensors for faint radiation, and can deploy more powerful telescopes in all wavebands (in space as well as on the ground). Equally important, theorists have access to burgeoning computer power: numerical simulations, a substitute for real experiments, are playing a crucial role. And without computers we couldn't analyse large surveys—for instance the wealth of data on large-scale structure that Jim Gunn and his associates have accumulated from the Sloan Survey.

Several lines of evidence now point towards some fundamentally new physics. For instance, there are the mysteries of 'dark matter' and 'dark energy'—most of the stuff in the Universe isn't made of ordinary atoms at all but is of quite unknown nature. Such developments have stimulated exciting research on the the interface between the 'inner space' of particle physics and the 'outer space' of cosmology.

A conceptual worry is sometimes raised: how can our universe have started off as as a hot amorphous fireball, and ended up intricately differentiated? This may seem contrary to the second law of thermodynamics. But it's actually a natural outcome of the workings of gravity. The expanding universe is unstable to the growth of structure, in the sense that regions starting off very slightly overdense have their expansion slowed by their excess gravity, and evolve into conspicuous density contrasts. Theorists can now follow a 'virtual universe' in a computer. The aim now is to delineate how, from simple beginnings, our cosmos transformed itself, over a timespan of 13 or 14 billion years, into the compex cosmic habitat we see around us, and of which we are part.

After half a million years, cosmic expansion had cooled the promordial radiation to around 3,000 degrees, and our universe was still fairly smooth. Thereafter, the primordial radiation cooled further, shifting into the infrared: the universe literally entered a dark age. Everything stayed dark until structures formed, and generated the 'first light' .

Thanks to the combined output from 8-10 metre optical telescopes the Hubble Space Telescope (HST), and sensitive probes of the x-ray, infrared and radio sky, astronomers have delineated the history of star formation, galaxies and clustering during the last 90 percent of cosmic history Our universe has by now been expanding for 13 or 14 billion years, but when it was a mere 1 billion years old, large galaxies had assembled.

Some of these have 'active' centres that shine brightly, indicating that huge black holes had already formed.

A lot of structure formation must therefore have happened even earlier—within the first billion years. Indeed the very first stars probably formed less than 100 million years after the big bang. These stars might have been very different from those we see today—perhaps at least 50 more massive than our Sun. And they would have formed in much smaller groupings than present-day galaxies.

With several collaborators, I am investigating the formative stage of cosmic structure—what happened in our universe when it was (in round numbers) between 1 and 10 percent of its persent age. A whole raft of questions arise: What were the first stars like, and how many of them form at each stage? How did the first black holes form? Are present-day galaxies the outcome of hierarchical mergers of smaller units? How much energy was pumped into intergalactic space at these early eras?

Via a combination of improved observations, and ever more refined simulations, we can hope for great advances in 'environmental cosmology'—elucidating how our elaborately structured cosmos emerged from a near-homogeneous early universe. I'm hopeful that we'll detect structures far beyond the most distant galaxies now known, and thereby probe still further back in time.

As well as being the grandest of the environmental sciences,cosmology is also a crucial part of fundamental physics. We may understand the evolution from a microsecond after the big bang to the present era, but we don't know what banged and why it banged—that is a challenge for 21st century cosmology.

The structure of our universe depends on a few numbers. These include the relative densities of baryons, dark matter and dark energy: we don't understand these ratios. Of specific relevance to large scale structure is a number Q, which measures the amplitude of the fluctuations in the early universe. These fluctuations are observed in the microwave sky and are the seeds for structure formation. If Q were substantially altered from its actual value of around 1/100,000, the outcome would be a universe where galaxies had very different morphology and the scales of non-linear structure were different. For some values of Q, no stars (nor any life) could exist.

What we've traditionally called our universe—the domain of space and time that we can in principle observe—may not be all of physical reality. Indeed, our big bang may not be the only one. Cosmic numbers (Q and the density of dark energy, for instance) may not be truly universal, but could take other values in domains that we can't observe. If things turn out that way—if the multiverse 'rings the changes' on the options —- it would remove the mystery of why our universe is characterised by a set of numbers that are rather arbitrary-seeming except for lying in the part of parameter space compatible with the emergence of complexity.

Each advance in science brings new mysteries into sharper focus. Cosmologists are now addressing questions that could not even have been posed in earlier decades. I'm confident that when the history of science is written from a balanced future perspective, the cosmological advances of the late 20th and early 21st century will be one of the most exciting chapters. It's a privilege to be a participant in this ongoing enterprise, and an honour to share in this 2005 award.

The Formation of the First Stars

Tom Abel, Stanford University, USA

Observations of the cosmic microwave background provide a detailed description of the thermal state and the density fluctuations which are the initial conditions for structure formation. With novel numerical techniques in cosmological hydrodynamics it has become possible to evolve these data forward in time to make predictions of the physical events that ended the dark ages. First small dark matter halos form at the free streaming length of the dark matter which may be as low as one earth mass. These small halos continuously merge to form larger objects. When they exceed the cosmological Jeans mass the primordial neutral intergalactic medium is drawn into the potential wells of these halos. Only when these objects grow by another order of magnitude does chemistry become fast enough so that molecular hydrogen gets formed in the gas phase. The near and mid-infrared ro-vibrational lines of these molecules provide now a significant loss of the thermal energy of the gas which in turn allows gravity to dominate the evolution of the gas. This cooling facilitates the collapse over 25 orders of magnitude in density necessary to form stars from gas at cosmological densities. I'll discuss in detail three dimensional calculations that include all these physical processes. These simulations predict the outcome of this collapse to be the formation of isolated very massive stars which dramatically impact the thermal and hydrodynamic state of the intergalactic medium around them.

Extremely Large Telescopes—Why and How

Torben Andersen, Lund University, Sweden

A generation of large optical telescopes with aperture diameters of 8-10 m is nearly completed and has boosted observational astronomy. At the same time, recent results have demonstrated that astronomy would benefit from much larger telescopes. Also, design experience seems to indicate that with new technology it will be possible to construct telescopes much larger than those existing today.

Science programs that would highly benefit from future telescopes with primary mirrors in the range 30-100 m include studies of planets in other solar systems, and formation and evolution of stars and galaxies.

World-wide, there are several study projects in progress to establish how the next generation of large telescopes and their instrumentation can be built. In the United States, a "Thirty Meter Project" has received significant study funding and the design of a 30 m telescope is well advanced, aiming at completion around 2015. Another US project, the "GMT", plans to build a 21 m telescope.

In Europe, two concepts have been studied. European Southern Observatory in Munich is proposing a 60-100 m telescope ("OWL"), whereas a team from five institutes in Sweden, United Kingdom, Spain, and Ireland, and led by a group in Lund, is studying a 50 m telescope ("Euro50"). It is believed that a European extremely large telescope could be ready in 2018-2020.

Extremely large telescopes will have a light collecting power many times higher than existing telescopes. Thanks to computer control systems, the form and position of optical elements will be controlled closed-loop, thereby correcting not only for internal telescope errors but also for blurring from the atmosphere. Extremely large telescopes will give pictures that are much sharper than possible before, and it is fair to say, that the new generation of telescopes will be as much of a revolution to astronomy as the construction of Galileo's telescope in 1609.

Evolution of Galaxies and Extremely Large Telescopes

Arne Ardeberg, Lund Observatory, Sweden and Peter Linde, Lund Observatory, Sweden

The study of cosmic diversity requires samples of all major morphological types of galaxies. The closest adequate sample is the rich Virgo cluster of galaxies at 16 Mpc. In the Galaxy, star clusters are prime laboratories for calibration of the evolutionary clock and the scales of distance and abundance. In other galaxies, they trace assembly and evolution and probe the influence of environments and interactions. Member stars are close to co-eval and co-distant with common initial abundances. They have similar extinction. Clusters are easy to isolate from disc populations and little affected by parent-galaxy orientation.

Probing galaxy evolution with clusters requires high spatial resolution and light collection. In the optical region, derived ages and abundances are robust and, further, the diffraction-limited resolution is high. An extremely large telescope (ELT) with adaptive optics (AO) allows evolutionary studies out to the Virgo cluster.

With uvby photometry for an open cluster as the starting point, we modelled and simulated a cluster and used it for ELT photometry and galaxy studies. The simulated cluster was placed at distances between 1 and 30 Mpc. Images were measured and magnitudes and indices analysed. Colour-magnitude and metallicity diagrams were constructed and ages and abundances determined from turn-off-point (TOP) photometry and m1 versus (b-y). We evaluated studies of galaxy evolution at different distances, depending on telescope aperture and point-spread function (PSF). Attention was given to the Strehl ratio and the AO PSF residual halo and their implications concerning spatial resolution and photometric quality.

For star-cluster photometry at Virgo distances with a 50 m ELT, we find that a Strehl ratio of at least 0.2 is needed, ratios of 0.3-0.5 are adequate and larger ratios excellent. Corresponding abundance studies require a Strehl ratio above 0.6. For open stellar clusters beyond 5 Mpc, the effect of the residual PSF halo is limited, as the cluster is, typically, located inside the halo. Adequate TOP photometry in Virgo need apertures of at least 40 m, while abundance studies require at least 50 m. Clusters located in thin disc populations are favourable.

With a 50 m ELT and proper AO and PSF, TOP photometry provides excellent age data for young stellar clusters in Virgo and adequate data up to 4 Gyr. For young clusters, reasonable abundance data can be derived. Image crowding is more serious than photon starvation. Older stellar clusters need further study, now in progress.

For young clusters beyond 50 Mpc, we evaluated integral colour data. Results with (b-y) as an age parameter are promising. Corresponding evaluation of integral colour indices for abundance are in progress.

Early Black Hole Formation

Melvyn B. Davies, Lund Observatory, Sweden

Massive black holes are thought to exist in the centres of all galaxies. I will review some of the possible mechanisms for the formation of these black holes. In particular, I will show how stars formed within a dense cluster are likely to undergo collisions.

Such collisions may lead to the production of very massive stars which, in turn, will produce black holes or neutron stars when they explode as supernovae. If there are a sufficient number of supernovae, a sub-cluster of black holes (and neutron stars) will form. I will describe the subsequent evolution of this sub-cluster.

One possibility is that one black hole becomes dominant as it accretes other black holes and neutron stars. Alternatively, the core of the sub-cluster may contract as binaries lose energy through the emission of gravitational radiation. This contraction may lead to a relativistic instability leading to the collapse of the core to form a single, massive black hole.

The Star Formation History of the Universe

David Elbaz, CEA Saclay/Service d'Astrophysique, France

While the formation of the "light elements"—hydrogen, helium, lithium and their isotopes—took place during the first three minutes after the Big Bang, the remaining "heavy elements" were formed in stars during the nearly fourteen billion years that followed until today. The history of the production of complex matter and of the so-called metal enrichment is therefore related to the star formation history of the universe. Although evidence was recently found for intergalactic stars, most stars were formed in galaxies. The deepest surveys of apparently empty patches of the sky have revealed the presence of galaxies up to very large redshifts, i.e. one billion years after the Big Bang. Since the lifetime of stars more massive than five solar masses is less than one hundred million years, the light radiated by those massive stars is a snapshot on the star formation activity of a given galaxy. Searching for the light radiated by massive stars in the past history of the universe, astronomers have been able to trace back its star formation history.

While present-day galaxies exhibit well defined morphologies, classified in three main families—Spirals, Ellipticals and Irregulars, this is less and less the case going back in time. The shape of distant galaxies reflects their formation history made of several encounters with other galaxies. Although less than 10 % of nearby galaxies lie in dense clusters, nearly all galaxies belong to over-densities with respect to the mean density of the universe, made of loose groups, filaments and sheets, the so-called large-scale structure of the universe. In the hierarchical galaxy formation paradigm, galaxies were formed through successive fusions of smaller entities. Hence their evolution reflects that of their spatial environment and the discovery that those mergers were associated to bursts of star formation suggested that the history of star and large-scale structure formation are intimately connected.

Paradoxically, the most luminous objects in the universe are associated with the growth, by the accretion of interstellar matter, of supermassive black holes located in the center of galaxies. With stars, they are the only two causes for the cosmic background light measured in the X-rays, optical, radio and infrared, after the Big Bang itself responsible for the cosmic microwave background radiation, or CMB. By resolving those cosmic backgrounds into individual galaxies, astronomers have made a striking discovery : in a universe dominated by dark energy and dark matter, even starlight and "black hole light" is mostly hidden to us by interstellar dust. Understanding the origin of those cosmic backgrounds will reveal the hidden face of the star formation history of the universe.

Near Field Cosmology—
The Milky Way and Galaxy Formation

Sofia Feltzing, Lund Observatory, Sweden

The origin and long-term evolution of stars and stellar systems are two of the great questions in modern astronomy. In particular the formation and evolution of galaxies from the very early ripples in the density distribution to the present day galaxies has attracted much effort, both observational and theoretical. The test that all models of galaxy formation and evolution must ultimately meet is the present day configuration of the Milky Way. Until we can reproduce the current spatial distribution, kinematics, and elemental abundances of stars and gas in the disks, halo and bulge of the Milky Way from an ab initio calculation, we cannot claim that galaxy formation and evolution is fully understood.

In this talk I will focus on how studies of dwarf stars in the solar neighbourhood can help us to distinguish between different formation scenarios, i.e. studying global (cosmological) process using the very local tracers of those events.

The primary targets for these investigations are detailed observations of the long-lived, "dull" stars that in their chemistry and kinematics provide excellent samples of the conditions of the gas from which they were formed. In this way, one can perform archaeological investigations -- trying to disentangle the different epochs of the past embedded in the data and in the end present a fullfledged history of how the Milky Way, our home in the Universe, formed and evolved to its present day configuration.

In particular I will discuss our own recent studies of the elemental abundance trends in large samples of dwarfs stars and through a comparison with current models of the formation of Milky Way like galaxies show how we can discrimenate between different formation scenarios for disk galaxies.

The Galaxy Formation—Large-Scale Structure Connection

Carlos Frenk, University of Durham, UK

The emergence of a cosmological paradigm in the past 2 decades provides a theoretical framework in which to understand the formation and evolution of galaxies. In this paradigm, the bulk of the universe is made up of dark matter and dark energy and cosmic structure grows through the gravitational amplification of small perturbations seeded when the universe was very young. Cosmological N-body simulations provide the means to investigate the clustering evolution of the dark matter and I will present results from the recently completed "Millennium" simulation, the largest cosmological simulation of its kind to date. The simulation provides accurate information about the formation paths, number density evolution and clustering properties of the dark matter halos in which gas will eventually cool and collect to make galaxies. I will then discuss the more complicated physical processes thought to be responsible for the formation of the luminous components of galaxies. In particular, I will emphasize the role that central supermassive black holes play in limiting the luminosity of the brightest galaxies and thus in determining the galaxy luminosity function. A model of galaxy formation can be grafted into the Millennium simulation in order to investigate the clustering properties of galaxies. I will conclude by comparing these theoretical predictions with obsevational data, particulary with the "2-degree" galaxy redshift survey.

Dark Matter in the Universe

Katherine Freese, University of Michigan, USA

I will begin by reviewing the evidence for Dark Matter in the Universe, as well as the candidates for dark matter. At most 20% of the dark matter in galaxies can be in the form of MACHOs (Massive Compact Halo Objects); the remainder appears to be some unknown exotic component. The most sensible candidates from the point of view of particle physics are axions and WIMPs (Weakly Interacting Massive Particles), where WIMPs may be supersymmetric particles. Three recent claims of possible detection of WIMP dark matter are tantalizing and will be discussed: the DAMA annual modulation, the HEAT positron excess, and gamma-rays from the Galactic Center. In addition, I will discuss the dependence of signals in detectors on the mass distribution in the Galactic Halo. In particular, the Sagittarius stream can be a smoking gun for WIMP detection.

The Role of the Sloan Digital Sky Survey and Future Large Optical Surveys in Cosmology

James E. Gunn, Princeton University, USA

The field of cosmology has evolved from an exceedingly data-starved field driven almost entirely by theoretical ideas barely a decade ago to one today in which there exist vast, rich sets of still relatively undigested data which are being used to confront theoretical models in great detail. For the first time in the history of the subject the data are good enough to constrain the cosmological model with some precision. After decades of apparent inconsistencies based on the analyses of small, poorly understood data sets, essentially all of the good current data from a vast variety of sources suggest that the universe is adequately described by a single "concordance" model of an entirely different nature than envisaged by cosmologists a decade ago: one in which the energetics of the expansion are currently dominated by a cosmological-constant-like "dark energy", much more important at the present epoch than the dark matter which has been known for a long time to dominate the rest mass density. The nature of this component has joined the nature of the dark matter as the most pressing and difficult questions facing cosmology today.

The data from which these conclusions have been reached come from many sources, but the chief contributors have been studies of the cosmic microwave background, optical studies of distant type 1a supernovae, and large optical redshift surveys, most notably the Anglo-Australian 2dF survey and the Sloan Digital Sky Survey (SDSS) with which the author has been associated for many years.

Statistical studies of the large scale structure in the distribution of galaxies was one of the prime reasons the SDSS was initiated, and the results have more than satisfied our expectations. Additional and supporting data have come from unanticipated directions in the survey, including studies of the Lyman-alpha forest spectra in quasars and from statistical studies of weak gravitational lensing. The survey data have by no means been exhaustively analyzed; indeed, most of the conclusions reached so far have come from relatively small subsets of the survey data, which will not be all in hand for approximately two years. I will discuss the results and precision obtainable from the full survey, and will preview briefly the expected capabilities of planned next-generation optical surveys, most notably PanSTARRS.

The Intergalactic Medium as a Probe of Galaxy Formation and Cosmology

Martin Haehnelt, University of Cambridge, UK

Moderate amplitude density fluctuation in the photoioinized warm Intergalactic Medium are responsible for most of the absorption features making up the so called Lyman-alpha forest in the spectra of high-redshift QSO's. QSO absorption spectra can therefore be used to study the large scale distribution of matter and the interplay of galaxies and their starburst-driven winds with the Intergalactic Medium from which they form. I will review the properties of the Intergalactic Medium as probed by the Lyman-alpha forest and will discuss measurements of the shape and amplitude of the power spectrum of the matter distribution and what the tell us about the inflationary phase of rapid expansion in the early Universe and the nature of dark matter.

Mapping the Dark Matter Distribution through Weak Gravitational Lensing

Henk Hoekstra, University of Victoria, Canada

In recent years our accounting of the components that make up the universe has improved tremendously, thanks to accurate measurements of the cosmic microwave background and studies of the large scale structure in the universe. From these, and other observations, it has become increasingly clear that the universe is governed by the "dark side": most of the matter is invisible (a.k.a. "dark matter"). In addition the expansion of the universe is accelerating, driven by the even more mysterious "dark energy". Understanding the properties of the dark matter and dark energy are amongst the most important challenges of the coming years in physics and astronomy.

The study of the distribution of matter in the universe and its evolution can provide important clues about the nature of the dark side. However, most techniques that study the large scale structure of the universe rely on luminous objects as tracers. As a result, the interpretation of these observations depends on our understanding of how galaxies form. A more direct approach is to use the fact that matter (luminous or dark) in the universe deflects rays of light, an effect known as gravitational lensing. In the case of weak gravitational lensing the intervening matter in the universe gives rise to a slight alignment in the shapes of distant galaxies. By measuring these minute distortions it is in principle possible make a map of the dark matter distribution. However, the signal is noisy and the shapes of the faint galaxies are also changed by the atmosphere and the telescope optics.

In recent years our ability with which we can measure these minute distortions has improved dramatically, thanks to new cameras and better measurement techniques, and the field has developed rapidly. I will present recent results from a number of surveys, which demonstrate the excellent prospects for weak gravitational lensing as a leading tool in cosmology. Finally I will discuss what we can expect in the next few years.

Galaxies and Quasars at the Highest Redshifts

Richard McMahon, University of Cambridge, UK

Observations from both the ground and space are currently transforming our knowledge of the distant Universe. Quasars and galaxies have been discovered progressively from redshifts of around $z\sim3$ to $z\sim6.5$, corresponding to look back times 2.1 billion years and ~850 million years after the Big Bang. We are obtaining the first quantitative observational glimpses of this early phase in the cosmic history of star formation and black hole accretion, the formation of the first stars and super-massive black holes, and nucleosynthesis of the chemical elements. These observations are now reaching a critical era in the history of the Universe; the Epoch of Reionization which marks the change in the physical state of the Universe from a cold neutral phase (the so called Dark Ages) to the period when the Universe is filled with ionizing radiation due to the first stars and quasars (the Cosmic Renaissance).

I shall describe the recent technological developments and scientific results from both ground and space. This will include the recent Ultra Deep Field(UDF) and GOODS survey observations with the Hubble Space Telescope, combined with ground based optical spectroscopy that have discovered some of the most distant galaxies ever seen. I shall also describe recent results of surveys for distant quasars including the Sloan Digital Sky Survey(SDSS) and the follow-up observations of these quasars that indicate that they harbour super massive black holes with accretion rates of ~50-500 M_{sol}/year and host galaxies with star formation rates of ~500-1,000 M_{sol}/year.

I will also describe new surveys for higher redshift($z=7$-10) quasars and galaxies that exploit recent improvements in near infra-red detector technology and that will allow searches based on Lyman-α emission and Lyman continuum absorption in the wavelength range beyond 1micron.

Anomalies in the Standard Picture for Galaxy Formation and a Possible Remedy

P. James E. Peebles, Princeton University, USA

The ΛCDM cosmology passes demanding tests on the scale of the Hubble length, but it looks less impressive on the scales of galaxies.

I am particularly bothered by the predicted rate of merging at low redshift, which seems unrealistically heavy, and by the voids that to my eye are more empty in the real world than seems natural in the ΛCDM cosmology. A long-range scalar interaction in the dark sector may help remedy both problems while preserving the successes of the cosmological tests.

The Cosmic Background Radiation with Planck

Jean-Loup Puget, Institut d'Astrophysique Spatiale, France

The Planck satellite will provide the third generation mapping of the Cosmic Microwave Background from space following COBE and WMAP.

The angular resolution will be better by more than a factor of 2 and the sensitivity such that the accuracy of the temperature anisotropies will be limited only by the astrophysical foregrounds. Polarization measurements should allow to test for the first time the presence of primordial gravitational waves which should be produced if the early universe underwent an inflation phase at the time of the grand unification of interactions.

The removal of astrophysical foregrounds is of course of critical importance for the Planck project. Besides the galactic foregrounds, other components of the Cosmic Background needs also to be extracted from the data. These are of course of high cosmological interest.

The contribution of the background due to the integrated emission of all galaxies in the universe has been shown to be a powerfull observational tool for cosmology more than 30 years ago by Patridge and Peebles. The Planck satellite should bring an original contribution to this by detecting the anisotropies of the Cosmic far Infrared Background.

The instruments are in the final stages of construction and testing. The performances of the Planck survey can thus be assessed today with much better confidence. They will be presented.

The Dark Age—Cosmological Challenges and Prospects

Sir Martin J. Rees, Cambridge University, UK

Half a million years after the big bang,, cosmic expansion cooled the primordial radiation below 3,000 degrees, and our universe literally entered a dark age. Everything stayed dark until structures formed, and generated the 'first light' . How and when did this happen?

Galaxies and bright quasars have been detected out to redshifts exceeding 6. This corresponds to an era when the universe was about a billion years old. By then, the dark age was plainly over. In the Cold Dark Matter model, where structure builds up hierarchically, the first stars would form within 'minihalos' of around a million solar masses. Some such structures should already exist when the universe is 100 million years old -- long before any structures as large as galaxies had assembled.

The key question is what happened between redshifts of 30 or more, when theory suggests that the first stars form, and redshifts of 6, the largest we can currently observe directly.

What would be the very first stars be like? Calculations by various groups (eg by Abel and his associates) convincingly suggest much higher masses than are typical in star-forming regions today. Once the first stars have formed, they exert feedback that renders the subsequent evolution still more uncertain.

At redshifts of (say) 10 the typical halos and stellar aggregates would be much smaller than present-day galaxies. Such faint objects might be detectable behind a massive cluster of galaxies that acts as a gravitational lens. Detecting individual supernovae would be al challenge. However, if some early massive stars ended their lives as gamma-ray bursts, these hyper-luminous events would be detectable even at z = 20 or more.

Present-day galaxies are the outcome of a series of mergers. Did black holes form with the same efficiency in small galaxies (with shallow potential wells), or did their formation had to await the buildup of substantial galaxies with deeper potential wells? This issue is important because it determines the expected rate of gravitational wave bursts that could be detected by LISA, and whether there is a population of high-z miniquasars.

Reionization of the intergalactic medium started when the first stars formed (at z>30) but was not completed until z = 6. The fractional ionisation at all redshifts within this range, and the spatial structure of both ionized and neutral gas, is crucial for several key cosmological issues. Diffuse neutral gas can be probed via 21cm tomography -- a technique that will become feasible with the advent of LOFAR, and (in the less immediate future) of the Square Kilometre Array.

The Evolution of the Galaxy Population

Hans-Walter Rix, Max Planck Institute for Astronomy, Germany

After the Big Bang the universe was nearly homogeneous, simple and elegant. The present day universe exhibits a wealth of structures over a vast range of scales, from stars and planets on the (astronomically) smallest scales, to galaxies and to the large scale structure of the galaxy and dark matter distribution on the largest scales. Observing and understanding how this hierarchical structure arose driven by gravitational instabilities, in particular seeing when and how galaxies and the stars in them formed, has been a central longstanding goal of cosmology. Detailed direct observations are crucial for this question, as cosmological models have had notoriously little predictive power in this regime.

In principle the observational approach is simple: observing the galaxy population in a sufficiently large and very distant volume provides us, via the light travel time of 10^9 - 10^{10} years, snapshots of galaxies in the young universe, whose future fate is statstically reflected in the galaxies we see in the nearby, present-day universe.

The last decade has seen a revolution in actually implementing these "look-back" studies of the galaxy evolution, owing to a wide range of new ground- and space-based observatories. Observations now cover the epochs in which most of the stars in the Universe formed.

I will present an overview of what we know empirically about the evolution of the galaxy population from $\sim$10% in time after the Big Band to now, and will sketch what it tells us about how galaxies formed.

Upcoming experiments have the potential to crack the next frontier: how and when did the very first stars form.

Relation Between the CMBR and Large-Scale Structures

Licia Verde, University of Pennsylvania, USA

In the past few years the joint analysis of the Cosmic Microwave background (CMB) data and Large Scale Structure (LSS) data have produced spectacular confirmation of the standard cosmological model. This is only the last episode in the long journey of the development of modern cosmology, in which the milestones were set by the three scientists we are celebrating.

These milestones include the realization that a radio noise was the echo of the big bang; the understanding that the CMB should carry the stamp of tiny mass fluctuations that eventually developed into galaxies and galaxy clusters; the development of a statistical tools to study the large scale distribution of galaxies.

The standard cosmological model has many deep open questions such as "what is dark energy?", "what is the physical model behind inflation?".

Over the coming years, new cosmological data will provide ever more rigorous tests of the cosmological standard model. Observations of the CMB and LSS and the study of the formation and growth of cosmological structures will be fundamental in addressing these unanswered questions.

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The Academy has about 350 Swedish members of whom 167 must be under 65. There are also 167 foreign members. Members belong to one of the Academy's ten classes.

The head of the Academy is the President, assisted by three vice-presidents—all elected to these honorary positions for a certain period. Together with the Permanent Secretary, who is a fulltime employee, they form a Presidium.

Academy work is carried on in the classes and in permanent or ad hoc committees. The Academy has a secretariat of about 20 employees, headed by the Permanent Secretary.

The Academy has bilateral agreements on exchange of scientists with academies in other countries, and represents Sweden in the International Council for Science (ICSU). The Academy also administers the Swedish national committees, which handle contacts with ISCU's international scientific unions.

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