Chaire internationale

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Leçon Inaugurale : *Faits et spéculations en cosmologie*
[en anglais, avec l'introduction en français]
le 20 novembre 2003.

Les enseignements : Cours sur *Cosmology : theories and observations*
en anglais du 10 décembre 2003 au 17 mars 2004.

Cosmology : Theories and Observations

There were thirteen lectures given, one a week from December 10, 2003 to March 17, 2004. (There were no lectures during the Christmas break, i.e., on December 24 and 31.) These lectures reviewed the present status of cosmology and took a critical look at the various results from theory and observations. The lectures received a good response with a steady attendance of around 50 participants. Each lecture was followed by a seminar. The seminars are listed separately with abstracts. Here is a non-technical summary of the lecture course. The technical details may be found in the book *An Introduction to Cosmology* (Cambridge) by Narlikar and other books listed in the bibliography that follows.

1. Historical Background

The lectures began with a historical background in which the early perception of a universe mostly confined to the Milky Way Galaxy with the Sun at its centre gave way to the present extra-galactic universe in which our location has no special significance.

On the observational side, in the 1920s Edwin Hubble gradually established this picture in which spiral and elliptical galaxies are found all over the universe. The erroneous observations of Van Maanen contradicting this picture were then set aside. In 1929, Hubble established what is today known as the Hubble Law which is generally interpreted as coming from an expanding universe. In this

Hubble spectroscopically determined the Doppler radial velocities of galaxies and found these to vary in proportion to their distances. The constant of proportionality is called the Hubble constant and it is denoted by H.

Parallel to this development, after proposing his general theory of relativity in 1915, Albert Einstein used it in 1917 to propose a model of the universe. This simple model assumed that the universe is homogeneous and isotropic and *also static*. For that was the general belief at the time. To obtain such a static model Einstein had to modify his equations to include an additional *cosmological constant term* which corresponded to a long range force of repulsion. In 1922-24, Alexander Friedmann, however, showed that one can obtain homogeneous and isotopic solutions without this term, but they describe an *expanding universe*. In 1927, Abbé Lemaitre also obtained similar solutions, but these were recognized as relevant to cosmology only after the 1929 result of Hubble. Einstein also decided that his cosmological constant was no longer needed and gave it up.

2. Early Cosmology

During the 1930s, cosmologists led by Eddington and Lemaitre discussed the theoretical models of the expanding universe and all these led to the concept of a “beginning” when the universe was dense and very violent. Lemaitre called the state that of a *primeval atom*. Later, Fred Hoyle, an opponent of this idea referred to the state as of “big bang”, a name that caught on when the model became more popular.

The crucial effect in Hubble’s law was the redshift found in the spectra of galaxies and its progressive increase with the galactic distances. This effect can be very well quantified by showing that the elongation of the wavelength is equal to the factor by which the universe has expanded since light left the source. Thus redshift $z = 4$, means the wavelength has multiplied 5 (= 1 + 4) times and the universe has expanded five times its original linear size.

On the observational side, Hubble made unsuccessful attempts to fix the values of the mathematical parameters of the model by observing galaxies and counting them to larger and larger distances. The 5-metre telescope at the Palomar Mountain was proposed for this very reason as it was hoped to settle this cosmological problem.

In the 1950s radio astronomers began their attempts to solve this problem by counting radio sources out to very faint limits. Martin Ryle made various claims to have confirmed the big bang models. However, it later became clear that these radio surveys might tell us more about the physical properties of the sources rather than those of the universe.

3. The Early Hot Universe

In the mid-1940s, George Gamow started a new programme of studying the physics of the big bang universe close to the big bang epoch. For example, calculations showed that the temperature of the universe, infinite at the big bang, dropped to about ten thousand million degrees after one second. In the era 1-200 second, Gamow expected thermonuclear reactions to play a major role to bring about a synthesis of the free neutrons and protons that were lying all over the universe. Were all the chemical elements we see today in the universe formed in this era ?

This expectation of Gamow turned out to be incorrect. Only light nuclei, mainly helium could have formed this way. The heavier elements could, however, be formed in stars, as was shown later by the comprehensive work of Geoffrey and Margaret Burbidge, William Fowler and Fred Hoyle. Today it looks as if the light nuclei were made in Gamow's early universe, as the stars do not seem to be able to produce them in the right abundance.

Apart from this evidence, there was another prediction made by Gamow's younger colleagues, Ralph Alpher and Robert Herman, namely that the radiation surviving from that early hot era should be seen today as a smooth Planckian background of temperature of around 5K. This prediction has been substantiated. In fact in 1942, McKellar had deduced the existence of such a background of temperature 2.3K from spectroscopic observations of CN and other molecules in the Galaxy. This result was not widely known or appreciated at the time. In fact it was the serendipitous observation of an isotropic radiation background in 1965 by Arno Penzias and Robert Wilson that drew physicists and cosmologists to the big bang model in a big way. Penzias and Wilson found the temperature to be 3.5K.

4. Physics of the Early and Very Early Universe

The cosmic microwave background radiation (CMBR) has prompted many physicists to look in depth at the physics of the post and pre nucleosynthesis era. For example, as the universe cools down, the chemical binding can become important and trap the free electrons into protons to make neutral hydrogen atoms. This eliminates the major scattering agency from the universe and radiation can subsequently travel freely. Calculations show that this epoch was at redshift of around 1000-1100.

If instead we explore epochs *earlier* than the nucleosynthesis one, we would encounter larger temperature and more energetic activity. This has attracted particle physicists to the big bang models for here they have a possibility of testing their very high energy physics. The very early epochs when the universe was 10^{-38} second old had particles of energy so high that the might have been subject to the grand unification scheme which could therefore be tested. Energies required for such testing are, however, some 13 orders of magnitude higher than what can be produced by the most powerful accelerators on the Earth.

Such a combination of disciplines is called *astroparticle physics.* One of its most influential "gifts" has been the notion of "inflation". This is the rapid exponential expansion of the universe lasting for a very short time, produced by the phase transition that took place when the grand unified interaction split into its component interactions (the strong and electroweak interactions). Inflation is believed to solve some of the outstanding problems of the standard big bang cosmology, such as the horizon problem, the flatness problem, the entropy problem, etc.

5. Dark Matter and Dark Energy

One of the conclusions of inflation is that the space part of the universe is flat. Theoretically it requires the matter density to be $\rho_c = 3H^2/8\pi G$. Here H is the Hubble constant and G is the gravitational constant. This value, sometimes known as the *closure density*, leads straightaway to a conflict with primordial nucleosynthesis which tells us that at this density there would be almost no deuterium produced. Even if we ignore inflation, and simply concentrate on the empirical value of matter density determined by observations, we still might run into trouble.

For, while the visible matter in the form of galaxies and intergalactic medium leads to a value of density which is less than 4 % of the closure density, there are strong indications that additional *dark* matter may be present too. The adjective "dark" indicates the fact that this matter is unseen but exerts gravitational attraction on visible matter. Such evidence is found in the motions of neutral hydrogen clouds around spiral galaxies and in the motions of galaxies in clusters. Even this excess matter would cause problem with deuterium.

To get round this difficulty, the big bang cosmologists have hypothesized that the bulk of dark matter is *non-baryonic*, that is it does not influence nucleosynthesis. Writing the ratio of the density of non-baryonic matter to the closure density as Ω_{nb} and the corresponding ratio for baryonic matter as Ω_b, we should get as per inflation $\Omega_{nb} + \Omega_b = 1$. Thus if the baryonic matter is 4 %, the non-baryonic matter should be 96 %.

However, even this idea runs into difficulty as there is no direct evidence for so much dark matter. A solution is provided, however, by resurrecting the cosmological constant that Einstein had abandoned in the 1930s. If we include the cosmological constant also, then we may ascribe a certain energy density to it and include this addition in the density budget. Thus we now get something like : $\Omega_b = 0.04$, $\Omega_{nb} = 0.23$, and $\Omega_\Lambda = 0.73$. This extra energy put in is called *dark energy.*

6. Structure Formation

These issues are important to the understanding of how large scale structure developed in the universe. To this end, the present attempts assume that small fluctuations were present in the very early universe and these grew because of inflation and subsequent gravitational clustering. Various algorithms exist for developing this scenario. One of the basic inputs is the way the total density is split up between baryonic, non-baryonic matter and dark energy. A constraint to be satisfied is to reproduce the observed disturbances produced in the CMBR by these agents. For, observations of small inhomogeneities of the CMBR rule out various combinations and also suggest what kind of dark matter (cold or hot or mixed) might be required.

7. Observational Tests

Like any physical theory cosmology also must rely on observational tests and constraints. There are several of these. The course reviewed (a) the measurements of Hubble's constant, (b) the study of redshift-distsnce relation to large redshifts, especially using Type Ia supernovae, (c) the counts of radio sources and galaxies, (d) the angular diameter redshift relation, (e) the ages of old objects like stars and galaxies, (f) the abundances of light nuclei, (g) the CMBR spectrum and inhomogeneities and (h) the large scale structure observed today.

It is seen that the present observational situation is at best confused. While (b), (f) and (g) seem to suggest a model with rather precisely required proportions of baryonic, nonbaryonic matter and dark energy, the uncertainties and conflicts encountered in the rest of the tests makes the issue very much open.

This is why there appears to be need for new ideas in cosmology especially alternative scenarios that follow very different tracks from the above standard scenario. The seminars that followed reported on some alternative models as well as on current observations and aspects of standard cosmology.

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4. Jean-Marie SOURIAU : *Cosmologie matière-antimatière*
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5. Laurent NOTTALE : *Cosmologie à relativité d'échelle*
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7. Pierre BINETRUY : *Supersymetrie et cosmologie*
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