of this kind is called 'closed'. If the mean density is less than critical, the universe will expand forever, and is called 'open'. The dividing line between these two alternatives is a universe where the mean density is exactly equal to the critical density and in which the speeds of recession of the galaxies slow down ever closer to zero but do not become zero until the infinite future. This case is called the 'flat' universe (or the Einstein–de Sitter universe) because, in such a universe, space, on the large scale, has zero net curvature.

Whether the universe is open, flat or closed may, in principle, be determined by measuring the rate at which the expansion is decelerating or by determining the mean density of matter and radiation in the universe. Although many theoretical cosmologists favor 'flat' or 'closed' models, and the observational data are far from conclusive, the balance of recent evidence appears to favor the open model.

See also: Big Bang theory, cosmological model, cosmological principle, deceleration parameter, expanding universe, Hubble constant, inflationary universe, redshift, steady-state theory.

Cosmology: A Brief History

Cosmology is the branch of astronomy that deals with studies of the large-scale structure of the universe. Observationally it requires data on the most remote objects while theoretically it demands the largest possible extrapolations of the basic laws of physics. Despite these severe constraints, cosmology has of late emerged as a very important branch of science where predictions can be made and tested.

When did modern cosmology begin? Indeed, one should go back to Isaac NEWTON, and his correspondence with Richard Bentley from 10 December 1692, to 17 January 1693 (see Whiteside 1976). It is interesting to read Newton's attempts to construct the model of a homogeneous and isotropic but static universe and his realization that it is unstable. Later attempts within the Newtonian framework, before relativity came on the horizon, were by C Neumann and H Seeliger during 1895–1896. In 1934, W H McCrea and E A Milne demonstrated how Newtonian ideas of gravitation and dynamics can be suitably adapted to give standard models of relativity.

The advent of the GENERAL THEORY OF RELATIVITY in 1915 offered a possible resolution of the conflicts which were beginning to surface between the Newtonian laws of dynamics and gravitation and SPECIAL RELATIVITY. General relativity linked the phenomenon of gravitation to the geometry of space and time. Only 2 years after he proposed the theory, ALBERT EINSTEIN made a bold attempt to apply it to construct a model of the entire universe.

Like Newton, Einstein also found that a static model was not permitted by his 1915 equations of relativity and introduced the so-called COSMOLOGICAL CONSTANT, λ, which implied (in the Newtonian approximation) a repulsive force that varied directly with distance. The static model that emerged required the universe to be closed. Einstein felt that the emergence of such a model was a demonstration of a unique and consistent relationship between spacetime geometry and the matter contents of the universe.

However, a paper by W DE SITTER in the same year demonstrated that the model was not unique. de Sitter found a model universe which was empty but expanding. Although it was considered esoteric at the time, this model has played a key role in cosmology on a number of later occasions.

In the second decade of this century, there was no systematic study of galaxies, although, by 1914, observers of diffuse nebulae, like V M Slipher, had reported nebular shifts, mostly redshifts, that indicated a radial recessional motion of these nebulae. However, despite these findings, the general belief in a static universe was quite strong and de Sitter's solution was treated more as a curiosity. Indeed, in 1922–1924, A Friedmann and later in 1927 (independently) Abbé Lemaître obtained models of the expanding universe for which the cosmological constant was not required, but these were also ignored by Einstein and others.

Meanwhile, understanding of the universe on the observational front was also growing. In 1924 E P HUBBLE had established, through the use of Cepheid variable stars, that the Andromeda Nebula is so far away that it has to be extragalactic. Indeed in the next few years the existence of extragalactic nebulae as galaxies in their own right began to be established.

However, it was the announcement of the velocity–distance relation of these nebulae by Hubble in 1929 that turned the tide in favor of these models. For, after a careful analysis of data on nebular redshifts, Hubble arrived at what is today known as 'HUBBLE'S LAW', namely that the radial velocity of a typical galaxy away from us is proportional to its distance from us. More exactly, the data show that the redshift of a galaxy increases with its faintness. If the redshift is interpreted as Doppler shift and faintness as due to distance, then Hubble's law follows. Although there might be other interpretations of the data, all cosmological models had to take cognizance of this basic fact about the universe. Indeed it was later realized that in his 1927 paper Lemaître had predicted a linear velocity–distance relation of this kind.

Thus, soon after Hubble's law became accepted, Einstein saw that a static model was unrealistic and abandoned the cosmological constant as the 'greatest blunder' in his life. There were others, however, who thought otherwise and, even today, this constant continues to feature in cosmological literature. The reader interested in knowing who did what and when in those early days may wish to see the historical account by North (1965).

The big bang models

The assumption of homogeneity and isotropy allows the cosmologist to define a 'cosmic time'. The spatial sections at a given cosmic time are supposed to be homogeneous and isotropic. H P Robertson in 1935 and A G Walker in 1936 independently worked out the most general line element describing such a spacetime. Taking any observer as the local origin of spherical polar coordinates (r, θ, ϕ) and t for the cosmic time, the Robertson–Walker line element is given by

$$\mathrm{d}s^2 = c^2\,\mathrm{d}t^2 - S^2(t)\left[\frac{\mathrm{d}r^2}{1-kr^2} - r^2(\mathrm{d}\theta^2 + \sin^2\theta\,\mathrm{d}\phi^2)\right]. \quad (1)$$

The function $S(t)$ is the scale factor mentioned earlier: its increase with time signifies the expansion of the universe. The constant k in the above is a parameter specifying whether the space t = constant is of positive ($k = +1$), negative ($k = -1$) or zero ($k = 0$) curvature.

The simplest FRIEDMANN model is the Einstein–de Sitter model jointly advocated by Einstein and de Sitter (1932) which has $k = 0$. For pressure-free matter (often called dust) this model has $S \propto t^{2/3}$.

That the geometrical features of the model are linked to its physical matter contents is demonstrated by the different behavior of these models for different matter density ρ. Thus we define the following quantities:

$$H(t) = \frac{\dot{S}}{S} \qquad \rho_c = \frac{3H^2}{8\pi G} \quad (2)$$

as the HUBBLE CONSTANT and the critical density at epoch t. We will denote their values at the present epoch t_0 by suffix zero. The density parameter is defined by

$$\Omega = \frac{\rho}{\rho_c}. \quad (3)$$

Then for the Friedmann solutions we have the following result: the universe is closed for $\Omega_0 > 1$ and open otherwise ($k = 0, -1$). Actually the case $k = 0$ is the marginally open case with $\Omega_0 = 1$; if the density exceeds ρ_c the universe is of the closed type. This is why the density ρ_c is called the closure or critical density.

In all models the scale factor was zero at some epoch in the past, commonly called the big bang epoch. At this epoch the curvature of spacetime was infinite and so was the density of matter and radiation in the universe. What about the future behavior of the universe? There the answer depends on the geometry of space. In the open models the universe expands for ever, with the scale factor going to infinity. In the closed models the scale factor attains a maximum value before decreasing back to zero.

In the above argument it is assumed that the matter in the universe is in the form of dust. This is a reasonable approximation at present when pressures are small and matter density far exceeds the density of radiation. However, one can show that

$$\rho_{\mathrm{matter}} \propto S^{-3} \qquad \rho_{\mathrm{radiation}} \propto S^{-4} \quad (4)$$

so that, at a sufficiently early epoch when S was small enough, the radiation term dominated over the matter term. This of course does not alter the earlier conclusion about the existence of the big bang epoch; in fact we now conclude that the universe was infinitely hot at that epoch.

In the Robertson–Walker spacetimes, the redshift is simply related to the scale factor. Calculation shows that a source with redshift z is being observed at an epoch when the scale factor of the universe was $(1+z)^{-1}$ times its present value. Observations at the present epoch indicate that matter density is at least $\sim 10^3$ times the radiation density. Thus we can estimate that the universe was radiation dominated at epochs prior to that of redshift $\sim 10^3$.

With the realization that the basic Friedmann models give an adequate description of the expanding universe, there have been many developments in cosmology in the last five decades that are based on these models. These developments may broadly be divided into investigations of (a) large-scale structure, through observations of discrete sources, (b) early history of the universe, through observations of relics, (c) evolution of the universe from particles to galaxies, (d) basic physical laws operating in the extreme conditions a few moments after the big bang, and (e) alternative cosmologies. We will briefly outline a few historical results.

Observations of discrete sources

A relativistic cosmological model uses curved spacetime and as such there are effects of non-Euclidean geometries that may, in principle, be observable. This was the expectation which prompted optical and radio astronomers of the 1950s and 1960s to push their observing capabilities to the limit. By observing the distributions of discrete source populations (galaxies, quasars, radio sources, x-ray sources, etc) the cosmologist hoped to find which of the various theoretical models came closest to reality.

The observational tests included (i) the measurement of Hubble's constant, (ii) the extension of Hubble's law to galaxies of large redshifts, (iii) the counts of galaxies and radio sources out to larger and larger distances, (iv) the angular diameter–redshift relation and (v) the relationship of surface brightness of a galaxy to its redshift. For details of these cosmological tests see recent textbooks and review articles, e.g. Sandage (1988) and Narlikar (1993).

The trend of such studies has shifted, however, from determining the geometry of the universe to determining how the discrete sources evolve. These studies are expected to tell us about the evolution of the physical environment of the universe, but so far no clear picture has emerged amidst a series of parameter-fitting exercises.

A key measurement that continues to be controversial is that of Hubble's constant. Hubble originally obtained the value of 530 km s^{-1} Mpc^{-1}, but in retrospect we find that there were several systematic errors in his measurements. For a long time, as the value of the constant steadily came down, there was continuing controversy about its true value, which was believed to lie between 50 and 100 km s^{-1} Mpc^{-1}.

Even today there are several calibration problems. However, it is only now that a clear appreciation of various practical issues is emerging, and different approaches are beginning to converge to a value of H_0 somewhere between 55 and 70 km s^{-1} Mpc^{-1}.

Relics of the early universe

The BIG BANG THEORY hinges on the fact that, at a time $t = 0$, the universe came into existence in a singular event. Thus no physical description of the original event is possible, although physical theories can examine the subsequent behavior of the universe. One of the early attempts to go close to the big bang epoch was made in the late 1940s by GEORGE GAMOW, who appreciated the fact that the early universe was radiation dominated, that is, its contents were made up of photons and other particles which were mostly relativistic in their energies. Thus, one could approximate the equation of state by pressure $p = \frac{1}{3}\rho$, both p and ρ being dependent on temperature as its fourth power, as for radiation in thermal equilibrium. Gamow and his collaborators Ralph Alpher and Robert Herman worked out the physics of the universe when it was around 1–200 s old. (A paper in 1948 by Alpher, H Bethe and Gamow on this topic led to it being called the 'α–β–γ' theory!)

Gamow had hoped to demonstrate that, in the high temperatures prevailing in this era, particles such as neutrons and protons would be synthesized into heavier nuclei, thereby determining the chemical composition of the universe. In the end, this work was partly successful in that light nuclei such as deuterium, helium, etc could be made in the primordial soup, but not the heavier ones such as carbon, oxygen and metals. Later it became clear from the important work of Burbidge, Burbidge, Fowler and Hoyle in 1957 (referred to as the $\mathrm{B^2FH}$ theory) that these nuclei are made in stars. Nevertheless, the abundances of light nuclei worked out according to the modern version of Gamow's pioneering attempt show a broad agreement with the observed ones.

A further check on the early hot universe scenario was the discovery in 1965 of the COSMIC MICROWAVE BACKGROUND by Penzias and Wilson. Gamow, Alpher and Herman had predicted such a background as the relic of the early era, although the discoverers had been unaware of these results. In their 1948 paper Alpher and Herman had predicted a relic background with an estimated temperature of 5 K. Present big bang calculations, however, cannot estimate the temperature of the background: it has to be taken as a parameter prescribed by observations. It should be mentioned that in the early 1960s R H Dicke and his colleagues had independently arrived at the Gamow–Alpher–Herman prediction of relic radiation and were setting up a detector for the radiation when they were anticipated by Penzias and Wilson.

The most spectacular development of recent years has been the success of the COBE satellite in measuring the spectrum (in 1990) and small-scale anisotropy (in 1994) of the microwave background. The background shows a black body temperature of 2.7 K and is highly homogeneous, with temperature fluctuations $\Delta T/T \sim 6 \times 10^{-6}$.

The abundances of light nuclei and the microwave background, its spectrum and anisotropy have provided strong prima facie support for the big bang scenario. There were constraints and challenges too.

Evolution of structure in the universe

A major challenge in cosmology has been to demonstrate how, in the standard big bang model, first nucleons and leptons evolved out of more primordial particles and from them eventually the large-scale structures in the universe formed; all this in a manner consistent with the radiation fluctuations found by COBE.

Of particular interest in this work is the role of the inflationary phase first discussed independently by A Guth, K Sato and D Kazanas during 1980–1981. The basic idea is the following. The big bang universe was infinitely hot at $t = 0$, but its temperature dropped with time according to $t^{-1/2}$. In this process, the matter in it underwent a phase transition and its effect was, for a very brief period, to inflate the universe at an exponential rate, much like the old de Sitter universe. The changes in the spacetime vacuum generate a force that simulates the cosmological constant first introduced by Einstein. This is the force that 'drives' the universe so fast with an exponential growth at a time scale of around 10^{-36} s.

Most theories of structure formation rely on initial fluctuations as they evolve through INFLATION and their subsequent growth. The latter takes place through gravitational interaction and clustering. Here cognizance must be taken of the interaction of the growing lumps of inhomogeneities not only with the visible matter but also with DARK MATTER. In particular, the results are sensitive to the type of dark matter, 'cold' or 'hot' or a mixture of both.

Dark matter is the name given to matter that is not normally seen through any waveband of the electromagnetic radiation. It was FRITZ ZWICKY who in 1933, first pointed out the possible existence of the 'missing mass' in clusters of galaxies. However, it took nearly four decades for the astronomical community to catch up with him! In the 1970s, the studies of motions of clouds of neutral hydrogen showed that they were moving with near constant rotational speeds around a typical spiral galaxy, even if they were located at progressively larger distances beyond the visible mass of the galaxy. These flat rotation curves indicated that the mass $M(R)$ of a galaxy up to a distance R from its centre increases approximately in proportion to R even if R vastly exceeds the visible boundary of the galaxy.

Likewise, Zwicky's expectations about hidden mass in clusters were also borne out with the findings that the galaxies in a typical cluster were moving with such high speeds that if one uses the virial theorem for a relaxed cluster

$$2T + \Phi = \text{constant} \tag{5}$$

where T is the kinetic energy and Φ the gravitational potential energy, then one needs a lot of hidden mass to make up for the latter. What is this dark matter made of and how much of it exists in the universe? This important question has been hotly debated but remains unanswered.

The present cosmological model building has to take various constraints into account and, within the big bang framework, the need to resurrect the cosmological constant is being strongly felt. It is, however, correct to say that the model building exercise is yet to settle down to a well accepted set of parameters including the value of this constant.

Alternative cosmologies

From time to time there have been alternatives proposed to the big bang cosmology, although the majority of cosmologists have always believed in the validity of the latter. The STEADY STATE THEORY proposed in 1948 by H Bondi, T Gold and F Hoyle livened up the cosmological scenario by offering a clearly testable alternative. This cosmology had the spacetime geometry described by the model proposed by de Sitter in 1917, although the physical rationale was different. The discovery of the microwave background in 1965 robbed the theory of much of its credibility. Other major initiatives in the field were the Brans–Dicke cosmology proposed by C Brans and R H Dicke in 1961, as a theory with its origins in Mach's principle, and the cosmology proposed by P A M Dirac in 1973, based on attempts to explain the very large dimensionless numbers that appear in cosmology and microphysics.

Lately, in 1993, the steady state theory has been revived in the modified form called the quasi-steady state cosmology (QSSC), by F Hoyle, G Burbidge and J V Narlikar.

Conclusions

As the observational details about the universe become more and more focused, the big bang cosmology becomes more and more constrained. For example, one long standing discrepancy has not yet been resolved: the ages of stars in some very old globular clusters are in the range 12–15 billion years, which is larger than the timespan of the standard model! This is another reason for reviving the λ term, for its inclusion can increase the age of the universe.

In the last analysis, what cosmological theory survives would depend on how the observational challenges are met. Unlike the situation at the start of this century, when there were hardly any cosmological parameters to constrain the theory, we now suffer from the embarrassment of riches. Let the fittest theory survive.

Bibliography

Narlikar J V 1993, *Introduction to Cosmology* (Cambridge: Cambridge University Press)

North J D 1965 *The Measure of the Universe* (Oxford: Oxford University Press)

Sandage A 1988 *Ann. Rev. Astron. Astrophys.* **26** 561

Whiteside T (ed) 1976 *Mathematical Papers of Isaac Newton* vol 7 (Cambridge: Cambridge University Press) pp 233–8

J V Narlikar

Cosmology: Standard Model

COSMOLOGY in the modern sense of quantitative study of the large-scale properties of the universe is a surprisingly recent phenomenon. The first galaxy RADIAL VELOCITY (a blueshift, as it turned out) was only measured in 1912, by Slipher. It was not until 1924 that Hubble was able to prove that the 'nebulae' were indeed large systems of stars at vast distances, by which time it was clear that almost all galaxies had spectral lines displaced to longer wavelengths. Subsequent observations increasingly verified Hubble's (1929) linear relation between distance d and the recessional velocity inferred if redshift was interpreted as a Doppler shift:

$$v = Hd.$$

The theoretical groundwork for describing the universe via GENERAL RELATIVITY was already in place by the mid-1920s, so that it was not long before the basic observational fact of an expanding universe could be given a relatively standard interpretation. The main observational and theoretical uncertainties in this interpretation concern the matter and energy content of the universe. Different possibilities for this content generate very different COSMOLOGICAL MODELS. The purpose of this article is to outline the key concepts and practical formulae of importance in understanding these models, and to show how to apply them to astronomical observations.

Isotropic spacetime

Modern observational cosmology has demonstrated that the real universe is highly symmetric in its large-scale properties, but it would in any case make sense to start by considering the simplest possible mass distribution: one whose properties are homogeneous (uniform density) and isotropic (the same in all directions). The next step is to solve the gravitational field equations to find the corresponding metric. Many of the features of the metric can be deduced from symmetry alone—and indeed will apply even if Einstein's equations are replaced by something more complicated. These general arguments were put forward independently by H P Robertson and A G Walker in 1936.

Consider a set of 'fundamental observers', in different locations, all of whom are at rest with respect to the matter in their vicinity. We can envisage them as each sitting on a different galaxy, and so receding from each other with the general expansion (although real galaxies have in addition random velocities of order 100 km s^{-1} and so are not strictly fundamental observers). A global