The Teachers' File

COSMOLOGY: WHAT ONE NEEDS TO KNOW

by John R. Albright

Abstract. Cosmology, the study of the universe, has a past, which is reviewed here. The standard model—the Big Bang, or the hot, dense early universe that is still expanding—is based on observations that are basically consistent but which require additional input to improve the agreement. Out of the early universe came the galaxies and stars that shine today. The future of the universe depends on the density of matter: too much mass leads to the Big Crunch; too little leads to eternal expansion and cooling. The dark-matter problem prevents us from knowing which will be the fate of the universe. The limits of what may be called "scientific" are addressed.

Keywords: age of the earth; age of the universe; anthropic principles; Big Bang; Big Crunch; closed, flat, and open universes; cosmology; dark matter; galaxy; general relativity; Hubble expansion; inflation; Local Group; microwave background radiation; Milky Way; quantum mechanics; standard cosmological model; universe; Virgo Supercluster.

COSMOLOGIES FROM THE PAST

Cosmology is the study of the structure and origins of the entire universe. Prior to the twentieth century the observational and intellectual tools we use today did not exist; but that lack did not inhibit scientists, philosophers, and religious leaders from speculating about how the universe is put together (Sproul 1979; Bierlein 1994; Hetherington 1993). For centuries the word *universe* (or often *world* or *earth*) meant approximately what we today call the solar system, with the earth at the center of it. The paradigm

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shift from geocentric to heliocentric was not yet complete in Galileo's time; with his telescope, Galileo Galilei not only assembled evidence for heliocentricity but also observed that the Milky Way is not a continuous stripe but a collection of very many discrete stars.

As late as the early nineteenth century, Sir William Herschel (Astronomer Royal, discoverer of the planet Uranus) plotted a map of the Milky Way based on solid observation, showing the solar system at the center. We now know that the solar system is quite far from the center of the Milky Way, but Herschel may be forgiven his honest mistake: the galaxy apart from our local segment is obscured by clouds of dust, and there is still no way for us to see the center of the galaxy with visible light. We must rely on other parts of the electromagnetic spectrum—X rays, infrared, and microwaves—for our knowledge of the center, including the fact that it is far from us.

In the nineteenth century the physics community had a notion that the age of the earth and of the universe was quite young. The only mechanisms known then by which the sun or other stars could shine were simple: heating by gravitational compression and emission of electromagnetic energy by blackbody cooling. Geologists knew better. The age of the earth as estimated from the depth of the Grand Canyon is greater than the nineteenth-century guess at the age of the universe. Both ages were well in excess of the six thousand years claimed by some on the basis of a literalistic interpretation of the Bible (Burchfield 1990).

When Albert Einstein formulated his general theory of relativity in 1915, it was widely believed by scientists that the universe had always existed in basically the same form that we see today. Einstein realized that his equations do not admit a solution that corresponds to a static universe; therefore, he added a term—the cosmological constant term—and the modified equations could indeed describe a static universe (Bernstein and Feinberg 1986, 16). When subsequent discoveries showed that the universe is not static, Einstein repudiated the cosmological constant term and considered it the worst mistake of his career.

In 1920 it was still a matter of controversy whether the "nebulae" were part of our galaxy or whether they were "island universes" in their own right. The latter proved to be the case, and as a result the size of the universe became greater almost overnight. Then Edwin Hubble discovered that most of the other galaxies are flying away from us: the universe is expanding. The Einstein equations without the cosmological constant term give rise to solutions that exhibit this expansion, a fact that was discovered by Aleksandr Aleksandrovich Friedmann as early as 1922 and rediscovered independently by Georges Lemaître (Bernstein and Feinberg 1986, 92) and Arthur Eddington.

In the years since 1930 a number of competing models of the universe (Peebles 1993, 196) have been suggested, including E. A. Milne's cosmology (which is based on Newtonian gravity); the steady-state model of Hermann Bondi, Thomas Gold, and Fred Hoyle (based on the perfect cosmological principle: the universe looks about the same from any viewpoint and at any time); the plasma universe of Oskar Klein and Hannes Alfvén; the fractal universe of Benoit Mandelbrot; and the hot, dense initial state universe of Friedmann and Lemaître (often called the Big Bang model). The measurement of microwave radiation from what appears to be empty space (Bernstein and Feinberg 1986, 141) and the consistency of that radiation with the blackbody form of Max Planck have led to the abandonment of these models except that of Friedmann and Lemaître, which is now called the standard model.

The Standard Model

In its simplest form, the cosmology that has become standard has four main components (Peebles 1993, 5). (1) The distribution of matter on the largest scales is close to homogeneous. (2) The universe is expanding. (3) The dynamical theory that best describes the universe is the general theory of relativity. (4) The expansion of the universe came from an early state that was very small, very hot, and very dense.

1. Wherever astronomers look with their telescopes, they see objects in the sky. In the nearer range it is not true at all that matter has a homogeneous distribution. The solar system, for example, has nearly all its mass at the center, in the sun. The planets are almost in a common plane, the plane of the ecliptic, and there is very little mass elsewhere in the solar system. The stars in the galaxies are distributed in varied patterns but with large spaces between the stars; clusters of galaxies have massive regions with empty space between them. Still, at the largest distances that can be investigated, there are galaxies. No model of the universe that says "there is matter here, but nothing more beyond" can correspond to this basic observation.

2. The expansion of the universe is the only way to understand the observed redshifts of the majority of galaxies. Hubble's discovery was that light from other galaxies has undergone a shift toward lower frequencies and longer wavelengths, called the Doppler effect, which is expected when the source of any wave disturbance is receding from the observer. There are certain galaxies whose light is blueshifted, but they are in a small minority, and their motion in our direction can be accounted for on the basis of their rotation as part of a cluster of galaxies. A prime example is the Andromeda galaxy, the closest galaxy that is larger than our own Milky Way galaxy; we know it is coming our way, since its light exhibits a blueshift. Benchmarks for the Doppler shifts are provided by spectral lines for which the wavelengths can be measured with great accuracy in terrestrial laboratories. The hypothesis that the shifts come from the Doppler effect is in good agreement with the data.

3. Einstein's general theory of relativity was the basis for the calculations of Friedmann, Lemaître, and others. Isaac Newton's theory of gravity is simpler, but it is less elegant, and where it differs from Einstein's theory, the latter agrees better with observations. The two theories agree when the mass densities are small and when the gravitational forces are weak.

4. The strongest evidence for a hot, dense beginning to the universe comes from the uniformity of the microwave background, as observed first by Arno Penzias and Robert Wilson. Their results were later refined by others to show with exquisite accuracy that intergalactic space is filled with old radiation left over from a hot beginning but redshifted by the expanding universe into a distribution that corresponds to a temperature of 2.7 kelvins (Celsius degrees above absolute zero). The customary interpretation of these results is that the Friedmann-Lemaître model is basically correct: the universe began with a singularity in the Einstein equations (often called the Big Bang), out of which flow all of space, time, and matter.

TROUBLES WITH AND EXTENSIONS OF THE STANDARD MODEL

1. In order to understand the details of the distribution of mass in the universe, it is necessary to know where the mass is and what it is made of. Here lies a problem, since we do not really know the mass of our own galaxy, the Milky Way. Estimating the mass of the solar system is no problem, because it is very nearly true that all the mass is in the sun, and the planets go around it according to Johannes Kepler's laws that are derivable from Newton's laws, including gravity. For the solar system a graph of velocity versus distance from the sun follows the simple power law of Kepler. But for stars in the Milky Way the same graph is not consistent with the gravitational effects based on the stars we know to be present. The only way to account for the anomalies in the rotation curve is to assume that additional matter is present throughout the galaxy—matter that does not shine the way stars do, so it is invisible. This anomaly is called the "dark-matter problem." The same anomalous rotation curves are observed in galaxies other than ours. As a result, statements about the distribution of mass in the universe will be theory-laden. A reasonable question is, What is dark matter made of? Many well-thought-out answers have been put forth, and the correct answer may well be a combination of several of them. Competing models can be grouped into hot or cold dark matter. Examples of suggested dark matter are massive neutrinos, brown dwarfs, black holes, Jupiter-like planets, and species of particles thus far undetected at terrestrial accelerator laboratories.

2. The statement that the universe is expanding is beyond debate. The main question is how fast it is expanding, since the future of the universe depends critically on that rate. If all the galaxies appear to be receding from us, it could be asked, are we not then at a favored place at the center

of the universe? The answer is no; the usual explanation is that galaxies are like dots painted on a large balloon. As the balloon is inflated, all dots recede from all other dots, and none of them is at the center.

3. For most purposes in astrophysics, the general theory of relativity (GR) is a completely adequate descriptor of gravity. The principal exception is the extremely early universe, immediately after the Big Bang singularity, when matter was so tightly compacted that quantum mechanics (QM) is needed. The sad fact is that GR is not compatible with QM, since GR is a classical field theory, in which it is possible to know the position and momentum of an object at the same time. Such knowledge is incompatible with the uncertainty principle of QM. Furthermore, GR is a nonlinear theory, whereas QM is linear. Many ingenious efforts have been made to find a theory that reduces to GR and QM in separate limits, but the best that has been done so far is to make qualitative descriptions about how such a theory might look. The Big Bang singularity points to the heart of the problem, since the general theory of relativity says that it is a single point in space-time, a concept that is not permitted in quantum mechanics.

4. The microwave background provides strong suggestive evidence for a Big Bang followed by expansion of the universe. The main point of concern is the relative abundance of the lightweight chemical elements in the universe. By far the most abundant element is hydrogen, with helium coming in second. Mathematical models of the early universe predict that small amounts of deuterium (the heavy isotope of hydrogen) and lithium were made at the time of the Big Bang but essentially nothing else. More massive atoms had to be formed at significantly later times by other processes. Relative amounts of the four primordial elements can be calculated theoretically, and they can be measured in various ways. The agreement is not very good unless you make use of the concept of inflation (Guth 1997): shortly after the Big Bang the universe expanded with excessive speed for a time. The idea of inflation is not implied by other theories, and there is no unique way of representing it in detail, but in broad outline it answers questions and solves problems such as elemental abundance and apparent homogeneity.

The Next Step: Formation of Galaxies and Stars

Following the Big Bang the various forces of nature decoupled, inflation occurred, radiation dominated for a time, and then matter in the form of protons, neutrons, and electrons began to condense out of the dense and relatively homogeneous universe (Weinberg 1988; Kolb 1996), which was still rather small. All this activity took only a few seconds. Over the next several thousand years the material of the universe condensed even more to form atoms and to clear away matter to form the beautiful transparent intergalactic universe we can see at night.

Eventually, gravity caused the matter to coalesce into large clotted aggregations that became galaxies, in which formed the stars. Gravity pulled the stars into such tight sizes that they became very hot and dense, enough to begin the process of nuclear fusion by which hydrogen is turned into helium. Further action of stellar evolution led to the formation of elements heavier than helium but lighter than iron. In about five billion years some of the stars collapsed to form iron and even heavier materials and then exploded as supernovae to spread these materials through the local region of space. Our entire solar system contains plentiful remnants of such debris from a supernova that blew up more than five billion years ago.

We live on a planet that revolves around the sun, our local star. The solar system is part of the Milky Way galaxy, located closer to the edge of the galaxy than to the center. The solar system goes around the center of the galaxy. The Milky Way belongs to a cluster of almost thirty galaxies, called the Local Group. The Andromeda galaxy and the Milky Way are the largest members of the Local Group, which in turn is a member of the Virgo Supercluster. In spite of the alleged homogeneity of the universe at the largest scales, there is mounting evidence that everything is clustered and that, instead of being homogeneous, the universe has great voids and great concentrations of mass.

THE LAST STEP: THE END OF THE UNIVERSE

Cosmology is concerned not only with origins and structures but also with the ultimate fate of the universe. Three distinct scenarios can be distinguished: closed, open, and flat.

The closed universe (Barrow and Tipler 1989) is characterized by a mass density that is large enough that, although the universe has been expanding ever since the beginning, there is enough gravity that eventually it will be pulled back together. The galaxies will then be blueshifted as they come toward each other, and the universe will heat up with the contraction until finally it will end in the Big Crunch, the formation of a gigantic implosion that will mark the end of everything. The question arises, If this occurs, can the universe rebound and repeat itself with another round of expansion? Perhaps, but if so, it will have no memory of the earlier existence. It can then be asked, How do we know that this is the first (or second, or . . .) time around? The answer is that we do not know. Using classical Greek geometry as a metaphor, the closed universe can be called *elliptical*.

The open universe (Dyson 1979) has a mass density small enough that gravity cannot pull the universe into a Big Crunch, so things continue to fly apart. The galaxies will continue to be redshifted, and the expansion will lead to progressive cooling until everything in the universe is frozen. The behavior of such a universe is not periodic; it only goes around once. The geometric term for this situation is *hyperbolic*.

There are many ways for the universe to be open or closed, depending on the value of the mass density. The flat universe is unique, because it is the borderline between the other two kinds. It is nonperiodic, and it entails eternal expansion—but at the slowest possible rate. It maximizes the time available for life in the universe. The geometric term is *parabolic*.

It is reasonable to ask which of these three is correct. The data so far do not make a compelling case for excluding any of the three. The observational uncertainties are too large to give a definitive answer. We do not know enough about the masses of galaxies (recall the dark matter problem), and we do not have sufficiently accurate ways of measuring the distances to the farthest galaxies from us. Future refinements of measurements may be expected to resolve the problem.

Limits of Science

The subject of cosmology has not always been considered scientific. After all, it fails to satisfy the criterion of repeatability: a scientific experiment must be repeatable in someone else's laboratory. But there is only one universe, the one in which we live. We cannot go back and repeat the Big Bang as an experiment, nor can we build another universe to try changing the initial conditions. Since the discovery by Penzias and Wilson of the microwave background, old prejudices against cosmology have been set aside, and the subject is now quite respectably scientific.

It would not be appropriate here to review all the ramifications of the various anthropic principles (Barrow and Tipler 1989). The essential point is that the laws of nature and the conditions of the universe appear to be very finely tuned for the eventual development of living forms that are sufficiently complex that they are capable of contemplating themselves and the entire universe. Once again, we are dealing with a subject that was traditionally shunned by objective scientists because it was considered too close to religion; anthropic principles are quite close to classical design arguments for the existence of God. On the basis of science alone, it is not obvious that the universe has a purpose (Weinberg 1988); science does not rule out the possibility of a purpose, but neither does it require one.

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