AN OVERVIEW OF COSMIC EVOLUTION

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Abstract. Since chemical complexity and then life itself came about as part of the evolutionary history of the cosmos, it would be helpful to have an overview of that history. After an introduction to a few key concepts, several relevant topics in modern cosmology are reviewed. These include: the Hubble Law and the age of the universe; large scale structuring; galaxy formation and evolution; and cosmic chemistry.

1. Key Concepts

A preliminary time scale for the evolution of the universe is basic to our discussion. If we take the age of the universe as of the order of 10^{18} secs (we will refine this shortly) then the universe became transparent, the decoupling of radiation from matter, at 10^{13} secs. The Planck time is measured as 10^{-43} secs and inflation, of which we will speak shortly, occurred shortly after the Planck time. In the intervening period, from inflation to the present, stars and galaxies formed, structure in the radiating and non-radiating material developed and we came to be.

Cosmological distances are typically expressed as a measure of the redshift, z. The relationship between distance and redshift requires a cosmological model which gives the fundamental constants of the expanding universe. It is usual to adopt the Standard Model (Longair, 1996). Thus, at $z=0.1$ the distance is approximately 1.5×10^9 light years, at $z=1.0$, about 9×10^9 light years and at $z=10$, about 13×10^9 light years. When cosmologists refer to "high redshift galaxies" they mean those with redshifts greater than $z=0.1$. The most distant galaxies yet detected have redshifts of about $z=6.5$

When cosmologists say that the universe is "flat", they mean that in its expansion it is just on the edge of expanding forever or collapsing in upon itself. Among all the possibilities for the expansion rate of the universe, it is remarkable that it is "flat" and this requires explanation. In 1980 Alan Guth (Guth and Tye, 1980) first proposed that the universe inflated at many times the velocity of light very shortly after the Planck time. The energy source is found in quantum mechanical phase transitions in the early universe before there was matter, so that velocities exceeding that of light could occur. A schematic presentation is given in Fig. 1. In a non-inflationary universe, depicted at the top, when the universe was at $t=10^{-35}$ sec it had a radius of 1 mm, which is much larger than the horizon distance of the universe at that time. With expansion the horizon of the visible universe is at a distance of 10^{28} cm (based on an age for the universe of 13.7×10^{9} years). In an inflationary universe, depicted at the bottom, the universe inflated so that at $t=10^{-35}$ sec it had a radius of 3×10^{25} cm.Thus today it has dimensions which are much larger than the horizon distance of 10^{28} cm, the distance which light can travel in the total age of the universe. Our visible universe is, therefore, inserted in a "multi-verse" invisible to us. This, of course, raises the question of the verifiability or falsifiability of such a multi-verse. However, the first predictions of observational tests of inflationary cosmologies are now being made (Hogan, 2002).

2. The Hubble Law Revisited and the Age of the Universe

One of the most fundamental ways of measuring the age of the universe is to determine its expansion rate, the velocity of expansion with distance, and thus calculate when the expansion began. This is called the "Hubble Law" and it is illustrated in Fig. 2 where the velocity in kilometers per second is plotted against distance measured in millions of parsecs (one parsec equals 3.26 light years). The slope of this relationship, the Hubble constant H_O, is inversely proportional to the time when the expansion began and thus to the age of the universe. The best fit to the observations (dots) is $H_O = 67$ km/sec/megaparsec; extreme values of H_O are also shown. The scatter in the observations, which increases with distance, reveals serious difficulties involved in obtaining accurate measurements both of the velocities and of the distances. In fact, measuring velocities is quite straight forward since it simply involves measuring the shift in wavelength of spectral lines in celestial objects, Doppler shift or redshift. But it is the selection of the objects and the interpretation of the measurements that create difficulties. What one wishes to measure is the expansion in the space-time structure of the universe, the so-called "Hubble flow." To do this one must select objects that are participating in that expansion. This typically means measuring the redshifts of galaxies and clusters of galaxies. However, galaxies have their own peculiar motions in addition to their motion with the Hubble flow and clusters of galaxies have the peculiar motions of their member galaxies and the peculiar motion of the cluster as a whole. These difficulties are best overcome by measurements made for objects at very large distances where the expansion velocities are very large, so that peculiar velocities are an insignificant fraction of the total velocities measured. But then the difficulty arises in the measurement of distances, since the error in the distance measurement increases with distance. In fact, the whole case for getting an accurate measurement of the Hubble constant comes down to measuring astronomical distances. Even with telescopes in space, outside the perturbations of the earth's atmosphere, geometrical determinations of distances are accurate to only about 3,000 light years, three percent of the diameter of the Milky Way. The usual way to proceed beyond is to use the so-called photometric distance measurements, whereby we assume the existence of "standard candles" in the universe, classes of objects that have the same intrinsic luminosity, so that their measured apparent luminosity is the result of only the inverse square distance for light propagation. Hubble, for instance, first measured the distance to the Andromeda nebula by using Cepheid variable stars as a standard candle. In order, however, to measure to very large distances we need objects which are intrinsically very bright. In recent years use has been made of type Ia supernovae (Saha et al., 2001; Sandage, 2002). The progenitors of these supernovae are binary white dwarfs wherein mass exchange causes a nuclear explosion. It is remarkable that the peak brightness in these systems is quite constant considering the origins of the energy and the fact that each system results in the nucleosynthesis of different amounts of certain isotopes, for instance Ni^{56}. Recently three other non-photometric methods have been used to measure large distances: measurements of the size and optical depth of holes in the cosmic background radiation (CBR) due to the Sunyaev-Zeldovich effect, gravitational lensing and fluctuations at high resolution in the CBR. Gravitational lensing is of particular interest since it allows the rather accurate determination to a lensed galaxy at a very large distance. Cardone et al. (2002) have made a determination of the Hubble constant by the measurement of the time delays in the arrival of the four images from a distant galaxy. Since there are more than 50 multiply imaged systems known this promises to be an excellent way to obtain an independent measure of the Hubble constant. The result of all of the tedious measurements described above is a Hubble constant which translates into an age of 13.7 x 10^9 years for the universe.

3. Large Scale Structure. Clustering and Voids

Why is it important to know the large scale distribution of matter in the universe? The distribution of matter today is the inheritance of the fluctuations in the early universe, propagated to the current epoch according to a given world model, i.e. the fundamental parameters of the universe: deceleration or acceleration, matter and energy densities, including dark matter and dark energy, etc. So the large scale distribution of matter will be a test of how well we know those fundamental parameters. Since galaxies are the luminous tracers of the way matter is distributed, it is important to map the distribution of galaxies to large distances. Hubble Space Telescope has observed rich clusters of galaxies, containing thousands of galaxies, out to distances of 8 x 10^9 light years. The first large galaxy redshift survey was conducted at the Harvard-Smithsonian Center for Astrophysics in the 1980s (Geller, 1990). That survey plotted 1,065 galaxies in a slice of the universe whose outer edge was at 450 million light years. Later about 10,000 additional galaxies were measured. This survey already began to reveal the so-called "soap bubble" structure with large clumps of galaxies and large voids. In recent years large automated sky surveys have already measured redshifts for hundreds of thousands of galaxies. At the Anglo-Australian Observatory the Two-Degree Field (2dF) Galaxy Redshift Survey was completed in April 2002 (Colless, 2003). It plotted more than 200,000 galaxies out to distances of 3 x 10^9 light years and confirmed the soap bubble structure of the universe to larger distances. A detailed comparison of the galaxy distribution with the small scale temperature fluctuations in the CBR showed that the distribution of visible mass (galaxies) is an excellent tracer of the over all mass of the universe (including dark matter). It also confirmed that some unknown form of dark energy is the dominant constituent of the universe and is causing the universe to accelerate in its expansion. An even more ambitious survey, The Sloan Digital Sky Survey (SDSS), an international collaboration, is under way and will be completed in June 2005. It will have measured redshifts for 600,000 galaxies in addition to positions and 5-color photometry for 100 million celestial objects (mostly galaxies) over 6,600 square degrees or one-sixth of the sky (Frieman and SubbaRao, 2003).

What is the largest scale on which clustering of galaxies and voids occur? How does one determine this? The apparent sizes must be corrected for inaccuracies in distance determinations. For instance, galaxies that appear to be at the edge of a void may be foreground or background objects to the actual void. Statistical methods have been developed for "walking around" the edges of an apparent void and determining its actual diameter (Hoyle and Vogeley, 2002). The result is that the largest voids measure about 150 million light years in diameter, about 1500 times the diameter of the Milky Way. This result is confirmed by a detailed study of the 2dF Survey mentioned above (Roukema, Mamon and Bajtlik, 2002). A surprising result has been that intergalactic clouds have been found statistically to be as common within voids as elsewhere (Manning 2002). These clouds are discovered by the so-called "Lyman-alpha forest," a series of Lyman-alpha absorption lines of the light from distant quasars shifted into the visual spectral regions by the Hubble flow. These clouds may be either proto-galactic, galaxies in formation, or simply the dissipation of a gas cloud which failed to form a galaxy. At any rate voids are apparently not altogether empty!

An important issue is the change in structure with distance and thus with time since the Big Bang. The problem here is that there are two effects which tend to cancel out each other. Any clustering that begins will generally increase with time. That is the way gravity works. So we should see more clustering nearby. But as we observe to greater distances we preferentially see the more clustered arrays, since they are the brightest and more obvious. The surveys mentioned have not yet succeeded in separating out these two effects and providing an answer to the development of structure with time in the expanding universe.

4. Galaxy Formation and Evolution. The Rate of Star Formation

Did the nuclei of galaxies form first and then by their gravity assemble stars already formed elsewhere? Or did stars form within a galaxy as the nucleus and other galactic features were also forming. The most likely answer is both with one or other scenario dominating in certain types of galaxies. One model of interest starts with the collapse of a 10^{10} solar mass cloud at about 12×10^{9} years ago, just 1.7×10^{9} years after the Big Bang (Mangalam, 2001). As a core forms the first generation of massive stars also forms. Thus enriched material is supplied to a rotational disk which forms after 0.5×10^{9} years from the beginning of the cloud collapse. Stars continue to form in this disk, a second generation from material enriched by supernovae from the first generation, and the core continues to collapse to from a black hole of 10^{7} solar masses. The only reason that star formation can continue is that the supernovae heat energy is less than the binding energy or that the cooling time of the hot gas is less than the time to escape the halo. At the end of this process we have a black hole nucleus, a bulge, a halo and a disk in which star formation continues. These structures are typical for galaxies as we observe them, varying in how much one or other structure dominates in different galaxy types: elliptical, spiral, irregular, etc.

Since one of the principal reasons for the difference in galaxy types is the rate of star formation, it is important for an understanding of galaxy evolution to study star formation rates as a function of redshift or "look back time" in the expanding universe. A best representation using data from the ultraviolet to submillimeter wavelengths is shown by the solid line in Fig. 3 (Blaine 2001) where the star formation rate, _(z), normalized to z = 1.5, is plotted against 1+z. The maximum rate occurs at a look back time of about 10 x 10^9 years, 3.7 x 10^9 years after the Big Bang. However, there is almost certainly an undersampling at large distances where only very intrinsically bright objects can be seen at the wavelengths covered. For this reason an interesting attempt has been made to sample star formation by using gamma-ray bursts, since these are very energetic events both in gamma-rays and in the associated optical transient emission and since their progenitors are thought to be short lived massive stars (Lloyd-Ronning et al., 2002). The results of this study of 220 gamma-ray bursts is shown by the four histograms in Fig. 3. It is thought that gamma-ray bursts arise from either the mergers of massive stellar remnants (neutron stars and black holes; PaczyDski 1986) or from the collapse of massive stellar cores (hypernovae, PaczyDski 1998). In either case they apparently help us to sample massive star formation at early epochs. In Fig. 3 the two histograms extending to the bottom right are derived by considering the collapse model and those rising to the right top by considering the merger model. In each case the difference between the two histograms is of no significance to our discussion, since it considers the flatness of the initial mass function which is not of concern to us now. It is clear, however, that, whatever the interpretation of the massive progenitors of gamma-ray bursts, massive stars formed in the very early epochs of the universe, as early as 0.5×10^9 years after the Big Bang. This could not be determined by observations in the uv to submillimeter wave range (solid curve in Fig. 3). The universe was developing structure: stars, galaxies, even clustering, at a much earlier epoch than had been thought possible a few years ago.

5. Cosmic Chemistry

All chemicals, except for the lightest elements, come from nucleosynthesis in stars. In the very early hot universe hydrogen, deuterium, helium and a few other light elements were made, but, as the universe expanded and cooled down, hot spots which housed thermonuclear furnaces were required to generate the heavier elements. With the passage of each generation of stars the universe became more metal abundant. The heaviest elements come from supernovae explosions, the death of massive stars. In cool, dark clouds in the interstellar medium molecules, even somewhat complex ones, can form sometimes with the help of interstellar grains on whose surfaces they find fertile grounds for development. These grains are, of course, themselves assemblages of somewhat complex molecules. A great deal of terrestrial biochemistry takes place in liquid water. This cannot be the usual case in the interstellar medium. Table 1, taken from Ehrenfreund and Charnley (2000), lists organic molecules discovered thus far in the interstellar and circumstellar environments. Of particular interest are the studies of infrared absorption spectra to young stellar objects embedded in cold dense envelopes. The line of sight typically passes through a large column density of interstellar ices. An example is seen in the spectrum of the star W33A, taken by the Infrared Space Observatory (Gibb et al. 2000) and shown in Fig. 4 where the absorption features of several organic molecules are identified. In recent years there has been an ongoing debate about the possible biotic origin of the 3.4 micron absorption signature of C-H stretching modes found in an amazing variety of objects, as shown in Fig. 5 taken from Ehrenfreund and Charnley (2000): the solid line is for an infrared galaxy at a distance of about 9 x 10^9 light years; the points are for the center of the Milky Way; the dashed line is for an organic residue of the Murchison meteorite. It appears that certain activities in carbon chemistry occur throughout the universe and there may be a rather universal reservoir of prebiotic organic carbon. However, from a study of the whole spectral region from 2 to 20 microns Pendleton and Allamandola (2002) conclude that there is no evidence for a biological origin to the 3.4 micron feature.

6. Summary

Since the physical evolution of the universe has led through increasing chemical complexity to the origins of biotic systems, an overview of recent results in cosmology is proposed as a background to discussions of the chemistry which led to life. Various independent methods conclude that the age of the universe is 13.7 _ 0.2 x 10^9 years. For the first time in the history of these determinations a decimal point has been placed on the year in which we celebrate the birthday of the universe. This is due in no small part to the refinements in old methods and to the development of new methods for determining large distances in the universe. It has become increasing clear that quantum cosmology has claimed priority in our attempt to understand the origin of the universe and that an inflationary epoch occurred very soon after that origin. The large scale distribution of luminous matter has become much better known with ambitious redshift surveys of galaxies and it appears that the distribution of all gravitating matter, including dark matter, follows this distribution. The largest scale on which the universe clumps is about 1500 times the size of the Milky Way. Structure as we know it today: stars, galaxies, clusters of galaxies, developed much earlier than expected, within perhaps 0.5 x 10^9 years of the universe's origin and this claim is supported by recent measurements at high resolution of fluctuations in the cosmic background radiation. The rate of star formation is one of the principal elements in the development of structure and it now appears that many more massive stars were produced in the early universe than we had known previously. Organic chemicals are widespread in the universe, especially in star forming regions. There is increasingly persuasive evidence that numerous pathways of carbon chemistry are prevalent in the universe and that it contains a reservoir of prebiotic organic carbon. Other than what we find on the earth, there is to date no evidence that this has led to the formation of biotic systems.

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Figure Captions:

Figure 1. A schema of a non-inflationary (a) and an inflationary universe (b)

Figure 2. The Hubble Law interpreted as the expansion of the universe.

Figure. 3. The rate of star formation is plotted as a function of "look back time" for: observations in the ultraviolet to submillimeter wavelength range (solid line); for gamma-ray bursters interpreted as "collapsers" (histograms to the lower right); for gamma-ray bursters interpreted as "mergers" (histograms to the upper right). See text for further explanation.

Figure 4. Absorption spectrum in the line of sight to the protostar WW 33A.

Figure 5. The 3.4 micron absorption feature due to C-H stretching modes in various objects. See text for further discussion.