1 Birth and Ageing of the Material Universe

A. H. Bridle

INTRODUCTION

Any review of 20 billion years of the history of the entire material Universe in so short a space as this must drastically abbreviate and grossly simplify many subtle issues. Efforts to comprehend the nature and evolution of the astronomical Universe have sparked some of the most celebrated and heated scientific controversy of our time. Our awareness of the *existence* of galaxies, clusters of galaxies, quasars and other objects beyond the Milky Way is very recent and has brought a bewildering array of observations that challenges both modern science and philosophy.

Figure 1 illustrates the continuing development of Man's conception of the Universe with a plot of estimates of 'the age of the Universe' against the dates at which they were made. The plot begins with Archbishop James Ussher's famous summation of Biblical data, from which he concluded in 1658 that the world was created on Sunday, 23rd October, 4004 B.C.: the plot ends with a contemporary (1973) astronomical estimate of the 'expansion time' of the Universe.

I feel that it would be overly presumptuous to suppose that the last entry on Figure 1, unlike any of its predecessors, stems from an ultimately comprehensive and 'correct' world-view. This should be borne in mind in assessing everything that I have to say. The world-view I am going to outline is that of many, but not all, modern cosmologists; few of its generalisations are completely unquestionable. One day it may seem as laughably naive or as quaintly misguided as its predecessors seem today. Indeed, I hope that it *will*, because the continual expansion of Man's conceptual horizons that modern astronomy has brought about seems to me to be one of the most exciting intellectual stimuli that science has produced. I should not like to think that future generations might be deprived of such an exciting challenge.

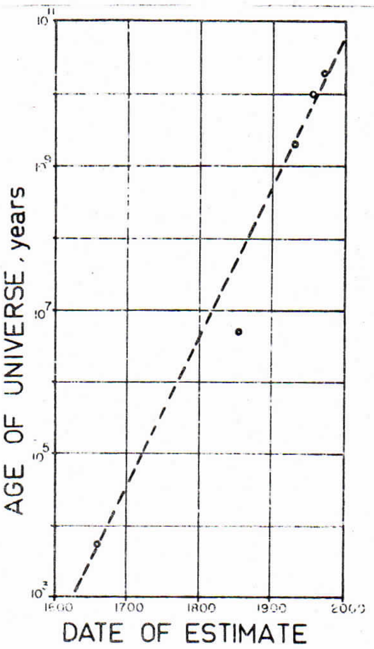

FIGURE 1: THE "AGE OF THE UNIVERSE" PLOTTED LOGARITHMICALLY AGAINST THE DATE AT WHICH IT WAS ESTIMATED.

THE UNIVERSE BEYOND THE MILKY WAY

Most textbooks of astronomy written in the later parts of the 19th Century contain abundant information on the aspects of the sky at different times of year, on the motions of the planets, and of their satellites and the tiny pieces of debris which litter our Solar System in the form of asteroids, comets, meteorites, etc. There is usually a discussion of time-keeping and the calendar, and finally an account of the properties of the stars and 'nebulae'. The 'nebulae' are the many faint, hazy patches of light seen among the stars in even a modest telescope. The French astronomer Charles Messier, a comet-hunter who grew tired of continually rediscovering such fixed patches of light, compiled a catalogue of them as early as 1781. They find little prominence in 19th Century texts: it was not until well into the 20th Century that it became clear that observations of some of these objects held the key to one of the greatest strides in our understanding of the Universe since the work of Copernicus in the 16th Century.

In the early 1800's, William Herschel showed the Sun to be a member of a flattened disc-shaped distribution of stars whose centre is now known to be about 30,000 light-years from the Sun. (The light-year is a convenient unit of distance for astronomy; it is equal to the distance travelled by a photon in a vacuum in one year, or about 5,880 billion miles.) The thickness of the disc of the Milky Way varies around it, but averages about 1,000 light-years. The flattening is now known to be due to a spinning motion of the entire assembly of stars: the Sun moves with a velocity of 134 miles per second around the central point, in an orbit which takes 250 million years to complete. The entire Milky Way contains about 100 billion stars, mostly arranged into a loose, tangled spiral-like pattern within the disc. (See Figure 2).

Herschel did not discover the full extent of this stellar system, for he was unaware of the presence of light-attenuating dust between the stars. This 'interstellar smog' restricts our view in most directions through the Milky Way to about 10,000 light-years. He and others speculated that many of the nebulae were simply distant, irresolvable clusters of stars within the Milky Way. There was only brief conjecture that the Milky Way might comprise less than the entire material Universe.

In the later years of the 19th Century, a 72-inch diameter reflecting telescope was constructed by an Irish nobleman, the third Earl of

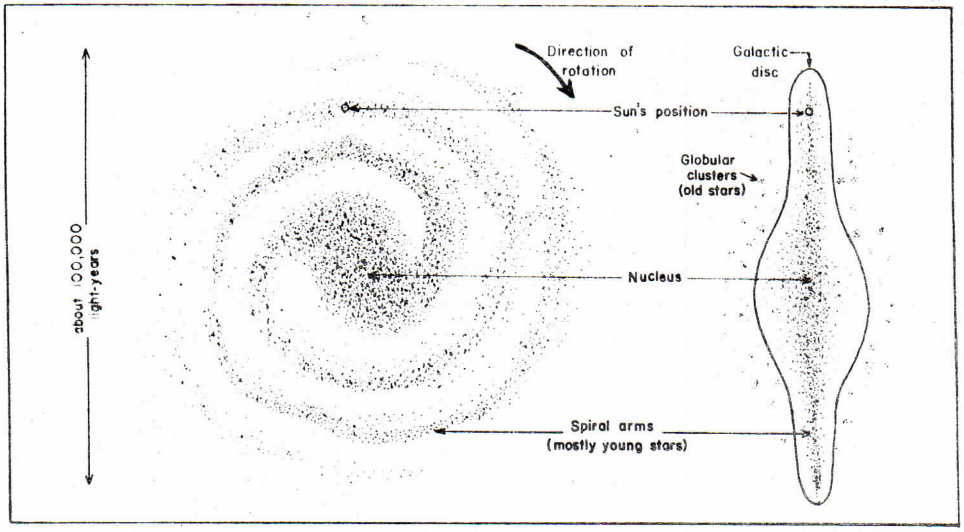

FIGURE 2: SCHEMATIC VIEW OF THE MILKY WAY AS SEEN FROM POINTS ON ITS ROTATION AXIS (LEFT-HAND DIAGRAM) AND IN ITS MID-PLANE (RIGHT-HAND DIAGRAM).

Rosse. With this telescope, for over 50 years the world's largest and most sensitive, he showed that many of the 'nebulae' had spiral forms, unlike those of any star clusters in the Milky Way. His observations were received with disbelief in some learned quarters; they were made before the days of telescopic photography and were presented as sketches from visual study at the eyepiece. They were, however, remarkably accurate in most respects.

It was not until the 1920's that Edwin Hubble, working with a 100-inch diameter telescope at Mount Wilson, California, demonstrated conclusively that these 'spiral nebulae' were complete stellar systems similar to the Milky Way at distances of millions of light-years beyond it. The nearest is in the constellation of Andromeda, over 2 million light-years away; it is the thirty-first object in Messier's catalogue, and is thus known as M31. It is a somewhat larger 'twin' of the Milky Way. The American astronomer Harlow Shapley introduced the term 'galaxy' to describe all such star systems: our own Milky Way is distinguished as 'the Galaxy'. In what follows, the Galaxy, not the Earth, must be thought of as our immediate environment - your home and mine.

Hubble's discovery of the true nature of the 'spiral nebulae' was the first in a brilliant career from about 1917 until his death in 1953. In that time, he laid the basis for a new understanding of the structure of the Universe. Galaxies, and clusters of galaxies, some of which contain hundreds of galaxies in regions tens of millions of light-years across, became recognised as the basic 'units' of a Universe wider than that imagined by any 19th Century astronomer. About 10 billion galaxies can be detected with the largest telescope presently in use, the 200-inch reflector on Mount Palomar: the most remote of these is more than three billion light-years from us.

Hubble's greatest discovery was that all spectral lines in the light from the fainter galaxies appear displaced towards the red in such a way that the proportional change in wavelength, $\Delta\lambda/\lambda$, is greater the fainter the galaxy. He interpreted the displacements of the spectral lines as Doppler shifts due to motions of the galaxies away from us, and used the faintness of each galaxy as a measure of its distance. He then concluded that the distant galaxies are all receding from the Galaxy with velocities proportional to their distances from it. The Universe, on the largest known scale, appears to be involved in an organised and simple motion of expansion. The profound question is - what brought this expansion about?

At first glance, the fact that the expansion is apparently centred on the Galaxy seems to imply a special place for the home of Man in the overall scheme of the Universe, and to signal a return to pre-Copernican notions of our centrality and importance. The analysis given in Appendix #1 dispels such grandiose ideas however: the universal expansion is such that it would appear this way from *any* vantage-point within it. It is precisely the one kind of expansion in which there are *no* privileged observers.

Hubble's observations, confirmed and refined by later workers, provide the basic root of all modern theories of the origin and development of the Universe. The expansion of the Universe is the most extensive collective phenomenon observed in the material world. What follows is a description of the history of the Universe as it is envisaged by the authors of the theory which has had the greatest success in describing not only this expansion, but also other recently-discovered features of the world beyond the Milky Way.

THE 'BIG BANG' THEORY

According to this theory, the early state of the Universe can be envisaged by imagining a reversal of the direction of time in the presently observed expansion, so that the galaxies would appear to collapse onto a central region. From the observed velocity-distance relation (Hubble's Law), it can be inferred that all the matter in the visible Universe was compacted into a very small volume about 20 billion years ago.

There is controversy over just how concentrated this early Universe may have been - its physical condition is clearly a colossal extrapolation from the available data - but it is visualised as a state in which the fundamental particles of matter (electrons, protons and neutrons) would be packed to a density comparable with that inside an atomic nucleus of more familiar matter. The temperature in this early state is visualised as some billions of degrees Kelvin. Matter could have existed only in the forms of individual fundamental particles; combinations to form nuclei or atoms would have been instantaneously disintegrated by collisions and by the inevitable intense background of radiation. The early Universe is pictured as a composite superdense 'gas' of fundamental particles and high-energy photons (γ-rays). Initially, the photons must have outnumbered the material particles by millions to one.

This 'primeval fireball' exploded. The moment of explosion, aptly called the 'Big Bang', is thought of as t = 0 in cosmic time, or in grander terms, the Moment of Creation. The matter and radiation of the fireball expanded outwards, initiating a motion of which the observed recession of the galaxies is the present-day relic. Some obvious questions to be asked of such a dramatic theory are:

How could the present universe of galaxies have evolved from such a pathological beginning? Is there any independent evidence for the drastic early phase from observations we can make today? To deal with these questions, we must consider the behaviour of the matter and radiation as the fireball expanded.

The Expanding Fireball - The Pre-Galactic Universe

For the first second after t = 0, the temperature would have been so high that most photons of the radiation had energies greater than the $E=mc^2$ equivalent of the mass of an electron at rest. In such conditions, electron-positron pairs could be created from the radiation by the process

$$\gamma + \gamma \rightarrow e^- + e^+$$

where each of the γ's is a photon at γ-ray energies, e^- is an ordinary negatively-charged electron and e^+ is a positron, the corresponding positively-charged antiparticle. This process is just the inverse of the electron-positron annihilation observed in terrestrial laboratories today.

Such processes of pair creation from the primeval radiation are thought to have brought about a short-lived thermodynamic equilibrium between the relative numbers of the fundamental particles - electrons (e), protons (p) and neutrons (n) through the reactions

$$\gamma + \gamma \rightleftharpoons e^- + e^+$$
$$n + e^+ \rightleftharpoons p + \bar{\nu}$$
$$p + e^- \rightleftharpoons n + \nu$$

In these processes ν and $\bar{\nu}$ represent neutrinos and anti-neutrinos respectively.

This bizarre equilibrium is thought to have lasted for about a second, after which pair creation ceased in the rapidly cooling radiation field. The significance of this short-lived era is that for a very wide range of possible initial conditions, the Universe at $t = 1$ second would have had the same ratio of neutrons to protons; this ratio plays a dominant role in settling the chemical composition of later matter.

For about half an hour after pair creation ended, the matter in the Universe would still have been hot enough for thermonuclear fusion reactions to occur, building protons and neutrons into the nuclei of the heavier isotopes of hydrogen and into nuclei of helium. (There would have been no atoms, just 'bare' nuclei and electrons, during this energetic era.) The early equilibrium established between the neutrons and protons would cause the chemical 'mix' emerging from the Big Bang - close to 90% hydrogen and 10% helium by number of nuclei - to be the same for widely differing initial conditions. The heavy nuclei that can be formed from helium under these primeval conditions turn out to be unstable, and essentially no nuclei heavier than helium could have been present in appreciable quantities when thermonuclear element synthesis (temporarily) ceased in the cooling Universe.

Thus, although we can do little more than guess at the state of the matter at $t = 0$ itself, a 9:1 hydrogen:helium mix seems especially probable for the matter emerging from the Big Bang only hours later.

The Formation of the Galaxies

The period roughly 100,000 years after the initiation of the expansion is also thought to have been important in the development of the Universe. By then, it would have cooled to about 3,000 degrees Kelvin, and the previously free electrons could have been captured by protons and helium nuclei to form atoms of hydrogen and helium. Once captured, the electrons could no longer scatter radiation and the Universe would have become transparent. Previously, the pressure exerted by the fireball radiation could have prevented chance irregularities in the matter from coalescing under their own gravitation; the only irregularities in the expanding fireball would have been in the form of oscillations, pressure waves or turbulence. Most such disturbances would have been attenuated by viscosity and by the development of shock waves, but some, of preferred sizes, would have escaped the damping processes.

Much recent work has been aimed at attempting to identify these preferred sizes: one at least appears to correspond to a mass of about 1000 billion stars, about that of the most massive known galaxies. The disturbances which survived the radiation-dominated phase of the expansion would be free to aggregate under the influence of their own gravitation after the Universe became transparent. From this time onwards the radiation could no longer 'hold the matter up' against its gravitation.

Under gravity, the density fluctuations in the early Universe could have condensed to make embryonic galaxies and clusters of galaxies. Some massive fluctuations might have collapsed under their own gravitation particularly efficiently, forming the compact objects with starlike telescopic images we call quasars. Some might even have collapsed so fully that photons can no longer escape from their surfaces, according to relativity theory. It is conceivable that matter in galactic quantities could be hidden from our view in such 'black holes'.

As the expansion continued, recognisable galaxies would have appeared, still flying apart from one another with the initial impetus of the explosion. The radiation background meanwhile became fainter and fainter, leaving these galaxies free to follow the evolutionary course dictated by their own gravitation.

The Relic Radiation

It is the residual radiation from the 'Big Bang' - its remaining electromagnetic whisper - that provides the most substantial independent observation in support of this cosmic *scenario*. The Big Bang theory makes three predictions about the radiation which should remain some 20 billion years after the initial explosion. Firstly, because the radiation was emitted by the condensed Universe in thermal equilibrium, the observed intensity should vary with wavelength like the radiation from an ideal thermal radiator, or 'black body'. Secondly, because the radiation fills the present Universe and our Galaxy is immersed in it, its intensity should appear the same in all directions. Finally, as a result of the expansion its effective temperature should now be very low, of order 3 degrees Kelvin. At such a temperature, the radiation should have its maximum intensity near a wavelength of 1 mm, in the microwave region of the electromagnetic spectrum.

One of the most remarkable developments in modern experimental cosmology was the observational confirmation of this faint isotropic background radiation essentially by accident during a piece of initially unrelated research. In late spring of 1964, Arno Penzias and Robert Wilson, of the Bell Telephone Laboratories at Holmdel, New Jersey, were studying cosmic radio signals with a large antenna set up as part of the 'Echo' satellite communications program. In making their measurements, they encountered an isotropic radiation background of unknown origin (to them), which they originally thought might be generated by imperfections in their antenna. It was only after discussions with the cosmologist Robert Dicke, whose group at Princeton was planning to build equipment specifically designed to locate and measure the relic fireball radiation, that the meaning of their observations became clear. Since then the Princeton group, and others, have confirmed both the isotropy and the apparent temperature of the observed radiation, from measurements at a variety of wavelengths. There is still some controversy about the accuracy with which it follows a black-body variation with wavelength, particularly in the infrared where it is directly measurable only by detectors taken above the Earth's atmosphere. Most recent measurements (1973) have however supported the interpretation that the observed radiation is universal and primordial and not merely some local phenomenon of no cosmological importance.

Helium

Helium is very difficult to detect in astronomical objects because most of its strong spectral lines lie in the ultraviolet region, which is screened by the Earth's atmosphere. Recent developments in radio spectroscopy, cosmic-ray physics and studies of stellar populations have however provided good estimates of the average helium abundance in regions of the Universe where we may expect the chemical composition still to be close to that of the 'primeval mix'. Big Bang theorists are strongly encouraged by the fact that the observed helium abundances in such regions are close to the 10 % proportion referred to earlier. This is not proof of the theory by any means, but it is an interesting piece of circumstantial evidence in its favour.

Radio Galaxies and Quasars

During the gravitational condensation of the fragments of matter to form galaxies and quasars, it appears that many of the more massive of them go through a phase of violent internal disturbance, during which they become the seat of intense radio emission. Modern radio telescopes can detect the resulting radio waves from these systems at immense distances, beyond the range of even the most powerful optical instruments. Because the radio waves travel at the finite velocity of light, the emission we receive now left these systems billions of years ago, and is thus a messenger of physical conditions in the cosmic past. Studies of the numbers of radio-emitting galaxies and quasars at different distances have provided evidence, not readily accepted by all cosmologists, that the radio sources were crowded together more closely in the past than they are now. This evidence, although still controversial, is also consistent with the history of the Universe proposed by the 'Big Bang' theory.

The Steady-State Theory

The most striking alternative to the 'Big Bang' theory is that originally advanced by Hermann Bondi, Thomas Gold and Fred Hoyle in the 1940's. At that time the 'Big Bang' description, unverified by the later observations described above, appeared to suffer from a crippling limitation. Because of an error in Hubble's estimation of the distances of the galaxies, the expansion rate of the galaxies was then thought to be much faster than the presently accepted value, so that the 'Big Bang' was placed only 2 or 3 billion years ago (see Figure 1 again). This conflicted with geological evidence that the age of the Earth is of order 5 billion years. Clearly the Earth could not be older than the Universe, so something was wrong.

Bondi, Gold and Hoyle sought a solution to this dilemma by postulating a Universe in which if the cosmic clock were reversed the galaxies would not fall back into a highly condensed state but matter would be removed to keep the mean density of material similar to that observed now. Conversely, new matter would have to be created in the 'real' expanding Universe (clock running forwards). The Moment of Creation of the 'Big Bang' model was replaced by a concept of continuous creation of matter, maintaining the average density of the Universe constant in time. In this scenario there would be no identifiable 'zero time', and thus no contradiction with the geological data.

The discovery of Hubble's error by Walter Baade in the 1950's really removed the need for the Steady-State theory, and the observations of the microwave background radiation dealt it a further blow. It might well be discarded but for its attractive symmetry and the comforting infinity it assigns to time. One of its proponents - Fred Hoyle - remains an outstanding critic of the 'Big Bang' theory, but admits that the Steady-State model no longer has the appeal it had when it was first proposed.

Most modern cosmologists are concentrating on working out the details of various versions of the 'Big Bang' type of theory, whose description was graphically summarised by its original proponent, the Belgian Abbé Georges Lemaître, who wrote: 'The evolution of the Universe can be compared to a display of fireworks that has just ended; some few red wisps, ashes and smoke. Standing on a cooled cinder, we see the slow fading of the suns, and try to recall the vanished brilliance of the origin of the worlds'.

WITHIN THE GALAXIES

We must now enquire how the details of our galactic 'cooled cinder', the Milky Way, came about.

According to the above picture of the development of the expanding Universe, the Milky Way began its career as a chance fluctuation in the material of the expanding fireball, its mass possibly determined by details of the fluctuation-damping mechanisms during the era dominated by radiation. After the radiation background cooled sufficiently, this fluctuation became free to fall in on itself under its own gravitation.

Other things being equal, this would have produced an approximately spherical condensation, but the proto-Milky Way had, by chance, a slight motion of rotation due to the turbulence of the overall expansion. The material of the proto-Milky Way thus had a finite amount of angular momentum. Once it began to collapse, it became effectively detached from its surroundings (although still participating in the overall recessional motion), and its total angular momentum was conserved.

The effect of conservation of angular momentum in a contracting body is familiar to anyone who has watched a figure skater 'spin up' by starting to rotate with limbs outstretched (Figure 3). On an ice surface, the skater forms a virtually isolated system - when the limbs are drawn in, angular momentum is conserved by a dramatic increase in the spin rate. The same phenomenon, on a quite different scale, took place in the formation of the Milky Way. The infall of the condensation under gravity parallels the pulling in of the skater's arms: the contracting condensation amplified its initial rate of spin. The skater, being flesh and bone, is not permanently affected by this result. The proto-Milky Way however, being gaseous, deformed the symmetry of its collapse as the spin-up progressed: the centrifugal effect of the spin perpendicular to the (originally random) direction of the spin axis opposed the self-gravitation of the condensation. Parallel to the spin axis, there was no such effect: the gravitational infall thus progressed more rapidly down the spin axis than across it, leading to a flattened result (Figure 4).

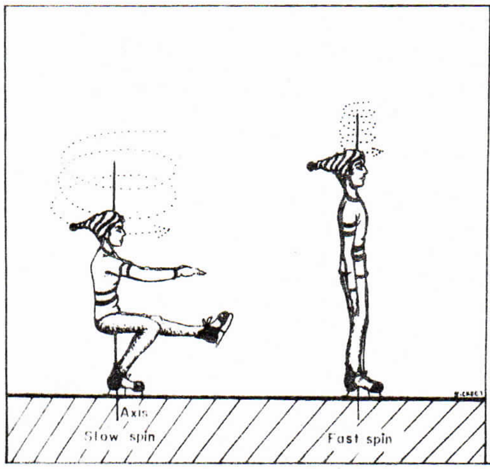

FIGURE 3: CONSERVATION OF ANGULAR MOMENTUM BY A ROTATING SKATER. AS THE LIMBS ARE DRAWN IN, THE SKATER'S ROTATION IS SPEEDED UP.

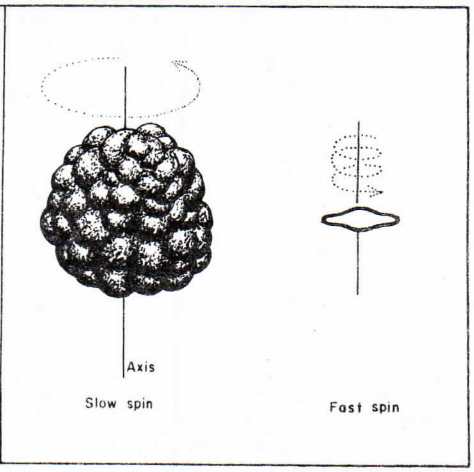

FIGURE 4: CONSERVATION OF ANGULAR MOMENTUM IN A GAS CLOUD CONTRACTING TO FORM A GALAXY. THE GRAVITATIONAL CONTRACTION IS OPPOSED BY CENTRIFUGAL EFFECTS PERPENDICULAR TO THE AXIS OF ROTATION, BUT PROCEEDS FREELY DOWN THE AXIS.

Not all galaxies have flattened, spiral shapes like that of the Milky Way; it seems likely that at least part of the variety of galactic forms (Figure 5) represents simply the variations in the amounts of the chance initial rotations acquired by the early condensations.

Within each proto-galaxy there are smaller sub-fluctuations. Gravitational attraction condenses these sub-fluctuations too, although as we shall see in the next lecture, the result of spin-up there appears to be fragmentation into double or multiple systems instead of an overall flattening. The sub-fluctuations become stars and star clusters.

Stars and the Origin of the Heavy Elements

The gas in each sub-fluctuation, drawn in by its own gravitation, begins to heat up. Due to the inability of the heavier nuclei to survive in the early stages of the fireball, the gas will initially be composed of hydrogen and helium in the primeval 9:1 mixture. As the 'proto-star' shrinks, the weight of the outer regions pressing down on the interior continuously raises the temperature at the centre of the condensation. When this temperature reaches about 100,000 degrees Kelvin, the hydrogen there becomes fully ionised. As the collapse continues, more and more of the gas becomes ionised while the central temperature continues to rise.

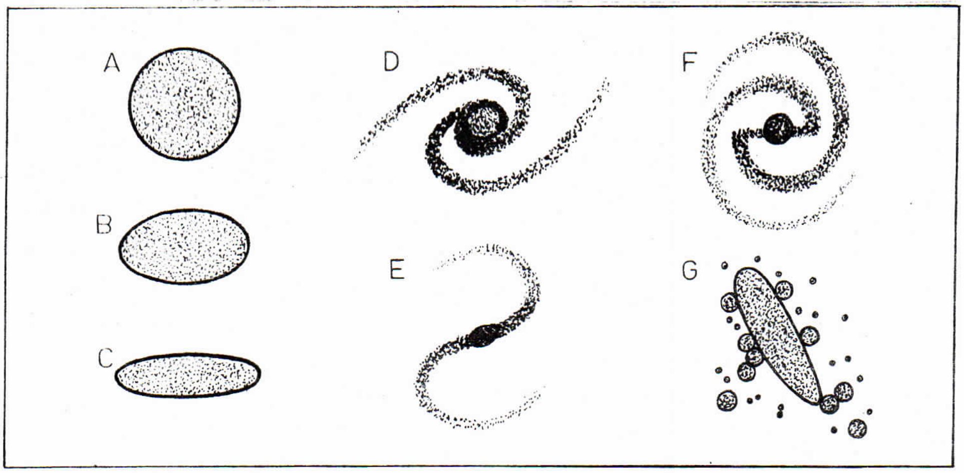

FIGURE 5: SCHEMATIC ILLUSTRATION OF GALAXIES OF DIFFERENT TYPES. A, B AND C ARE ARM-LESS ELLIPTICAL GALAXIES SHOWING DIFFERENT DEGREES OF FLATTENING. D AND E ARE SPIRAL GALAXIES SHOWING DIFFERENT TIGHTNESS OF WINDING OF THE ARMS. SPIRALS WITH TIGHTLY-WOUND ARMS TEND TO HAVE LARGE NUCLEAR REGIONS THAT RESEMBLE ELLIPTICAL GALAXIES. F IS A BARRED SPIRAL; THE ARMS START OUT PERPENDICULARLY FROM A LUMINOUS LINEAR "BAR". G IS AN IRREGULAR GALAXY.

Eventually the central temperature reaches about 20 million degrees; this temperature is critical, for then typical collisions between two protons in the ionised hydrogen can bring together enough kinetic energy to overcome the repulsion of their positive charges (with a little assistance from the quantum-mechanical 'tunnelling effect'). They can then come sufficiently close together that the powerful short-range nuclear attractive force can momentarily bind them together to form the nucleus of a highly unstable isotope of helium, He^2. This process annihilates a small amount of mass (the "mass defect" of the He^2 nucleus), and releases the corresponding amount of energy, calculable from the Einstein relation $E = mc^2$. This fusion of two protons is just the first step in a sequence of nuclear reactions which eventually culminates in the formation of stable helium nuclei, He^4.

Once the central compression of the 'protostar' raises the temperature this high, the condensation has a substantial internal energy source from nuclear fusion. By converting protons into helium nuclei, it can provide the outward flow of energy necessary to maintain a stable temperature gradient throughout the condensation. The temperature gradient maintains a gas pressure gradient which can support the distribution of the weight of the gas.

While the energy supply lasts, radiation flows outwards through the condensation and the collapse is halted. Simply, it begins to shine as a (temporarily) stable star. Starlight is thus the result of the very process of hydrogen-to-helium fusion which in Man's hands has proved so dangerous to our chances of survival.

The star has a finite amount of hydrogen which it can convert into helium. While this conversion proceeds, the gravitational collapse is halted. But even if the hydrogen were all converted to helium, gravitation would still be there and further collapse would then occur. In fact, the star's equilibrium is drastically affected well before even half of its mass is converted to helium. The course and time-span of its subsequent evolution depend on the initial mass of the condensation which formed the star.

For the Sun, the stable phase of hydrogen-to-helium fusion is still in progress and will probably continue for about 4 billion years; more massive stars suffer more severe gravitational squeezing and squander their energy supply more rapidly, in periods of a few millions of years. In any star, hydrogen-to-helium fusion eventually fails to supply the energy flow necessary to hold the star up against its own gravitation. The subsequent internal compression of the now-helium core of the star eventually forces this helium to fuse into heavier elements.

The energy yield from a given mass in nuclear fusion reactions decreases as heavier and heavier elements become involved, however, and once the star becomes seriously short of hydrogen its ability to 'buy time' against gravitational collapse is very much reduced. Increasingly heavy elements are manufactured deep within the star (Table 1). The most massive stars do this explosively, leading to <u>supernovae</u>, which spray the synthesised heavy elements out into the surrounding interstellar gas which has not yet formed into stars, leaving only a small remnant of the star behind.

<u>TABLE 1</u>: EXAMPLES OF NUCLEAR REACTIONS SYNTHESISING HEAVY ELEMENTS IN STARS

1.	Production of carbon	$He^4 + He^4 \rightleftharpoons Be^8$
		$Be^8 + He^4 \rightleftharpoons C^{12*} \rightarrow C^{12} + \gamma$
2.	Helium capture	$C^{12} + He^4 \rightarrow O^{16} + \gamma$
		$O^{16} + He^4 \rightarrow Ne^{20} + \gamma$
		$Ne^{20} + He^4 \rightarrow Mg^{24} + \gamma$
3.	Proton capture	$O^{16} + H^1 \rightarrow F^{17} + \gamma$
		$F^{17} \rightarrow O^{17} + e^- + \nu$
		$O^{17} + H^1 \rightarrow N^{14} + He^4$
4.	Heavy element "burning"	$C^{12} + C^{12} \rightarrow Ne^{20} + He^4$
		$\rightarrow Na^{23} + H^1$
		$O^{16} + O^{16} \rightarrow Si^{28} + He^4$
		$\rightarrow P^{31} + H^1$
5.	Neutron-producing reactions which can begin synthesis of other species by neutron capture	$\left(N^{14} + He^4 \rightarrow F^{18} + \gamma \right.$
		$F^{18} + e^- \rightarrow O^{18} + \nu$
		$\left. O^{18} + He^4 \rightarrow Ne^{21} + n \right)$
		$C^{12} + C^{12} \rightarrow Mg^{23} + n$
		$O^{16} + O^{16} \rightarrow S^{31} + n$

The Sun is not massive enough ever to become a supernova. Stars like it succumb to their own gravitation more sedately, ejecting relatively minor 'puffs' of material enriched with heavy elements into the interstellar gas, and leaving behind larger remnants of exceedingly dense material which gradually cool down and cease to emit light: these remnants are the so-called 'white dwarf' stars.

The explosive stages of stellar evolution are of far more interest to us than just as dramatic flares of distance points of light into temporary brillance: it is to these violent phases of the losing battle fought by every star against its own gravitation that we owe our very existence.

The chemistry of our protein-in-water life relies heavily on the presence of elements heavier than hydrogen. Many vital organs in the human body rely for their operation on trace quantities of the heavier metals. It is only during the mass-ejecting periods in the development of stars that these heavy elements, built up from the primordial hydrogen and helium, can be distributed into the surrounding regions of a galaxy. If they remained deep within the stars, they could never become parts of the bodies of living organisms such as ourselves.

Our own very local environment, the Earth and the other solar system planets, is much richer in heavy elements than the Universe as a whole. There is ample evidence, too detailed to be described here, that our Sun and similar stars did not form directly from the primordial material, but from subsequent fluctuations in interstellar gas in the Milky Way already enriched with heavy elements synthesised inside the earliest stars, and expelled from them towards the ends of their careers.

Every atom of a heavy element in your body and in mine was probably once inside a star (or stars) long since disrupted by the later stages of its (or their) gravitational contraction. Starlight is much more than just a pleasing attraction of the night sky - it is a direct consequence of the very process that started our form of life on the path towards its present state.

MAN AND THE UNIVERSE

In attempting to comprehend the architecture and evolution of the Universe we have begun to uncover, perhaps not surprisingly, the beginnings of our own history as well. Although we have only a very rudimentary understanding of many key phenomena - such as the formation of galaxies and stars - we are beginning to recognise that our environment is a small part of a changing, evolving cosmos whose own development brought us into existence and will ultimately settle our future.

Most of the Universe which I have described is a region we are unlikely to interact with other than just by observation and consequent theorising. Our study of it has however had a profound influence on our conceptualisation of our own existence.

Before the advent of modern astronomy, we could regard ourselves as the centre of Creation, endowed with special powers and significance. Now we must realise that we are mere atoms in the world of stars and the stars mere atoms in the world of galaxies. It is only in the last two million years that hominids have been present on the Earth. The light we see today from the nearest spiral galaxy, M31, was emitted when those hominids were first appearing. In the 20 billion years since the Big Bang, this is merely yesterday.

We also realise that we are in a *real*, not merely a poetic, sense children of the stars. The stuff of our bodies was made in them, as was the raw material for the ground under our feet. We preserve the delicate structures of our chemical existence by manipulation of energy that our host star radiates to buy time against its own gravitational collapse.

We should contemplate our relationship to the stars particularly carefully in view of the greedy demands of modern society for energy. All our energy supplies are by-products of stellar evolution. Before we became a technological animal, we relied mainly on stellar energy borrowed by photosynthesis in plants - energy stored in the food chain and in the forests. But our civilisation is increasingly using, on *its* short time-scale, energy in forms stockpiled on *astronomical* time-scales by stellar and planetary evolution. This is one reason for concern about the present direction of our social evolution. Man the organism is well-adapted to making use of the steady flow of energy from a hydrogen-fusing star. Man the organisation increasingly demands the exotica of catastrophic stellar deaths.

Even a cursory comparison of the human time-scale with the cosmic is enough to inspire alarm at the probable consequences of this demand. The individual of our species has great survival potential, able as he is to use intellect and manipulative skill to maintain a generally benign environment with only readily-available energy supplies. But our societies have multiplied our brawn without always producing, or even allowing, a correspondingly greater exercise of our collective brain. Could the discrepancy between the time-scale for us to escalate our demand and that for the flows of energy in the stellar cosmos signal a gross misdirection of our social progress? Could Man the organisation be acquiring a dinosaur-like ratio of brawn to brain?

Such questions will be explored in much detail in what follows.

For the moment, I must point out that even if we *can* survive the immediate consequences of our social trends - perhaps by rediscovering how to live on the continuously-replaceable stores of solar energy in the natural food chain, winds and meteorological cycles - we should still be deriving our energy supply from hydrogen fusion in the Sun. That process has a finite lifetime: the Sun itself is an evolving body.

Ultimately, in the wider Universe, the galaxies will recede, their stars will form, use up their nuclear fuel, and 'die'. The supply of interstellar gas which may form new stars will be continually depleted. The proportion of hydrogen in that gas will continually decrease.

The prospects for continuing star formation in the galaxies will therefore become bleaker and bleaker, as nuclear reactions in the heavier elements are not so capable of further energy release. The eventual state of the Universe, on this picture, is of 'dead' darkened galaxies of cold heavy-element stellar remnants, coasting further and further apart. On this Universal scale, we are not only tiny, fragile and recent: we are inevitably a transient phenomenon.

SUGGESTIONS FOR FURTHER READING

The evolution of the large-scale Universe, and of the Earth and Man within it, is the subject of a very readable book by Robert Jastrow - *Red Giants and White Dwarfs: Man's Descent from the Stars*, a Signet Science paperback.

More detail on studies of the distant Universe and of cosmology can be found in a book by Evry Schatzman - *The Structure of the Universe*, a World University Library paperback.

Galaxy formation has been reviewed by Martin Rees and Joseph Silk in an article entitled 'The Origin of Galaxies' in the June 1970 issue of *Scientific American*.

The experimental detection of the relic radiation is described by P.J.E. Peebles and D.T. Wilkinson in 'The Primeval Fireball', an article in the June 1967 *Scientific American*.

There is an eloquent discussion of radio sources and the status of steady-state cosmology in the book *Galaxies, Nuclei and Quasars*, by Fred Hoyle, published by Heinemann Press. This book also discusses some details of the processes of nuclear synthesis in stars.

Star formation is well reviewed by George Herbig, in 'The Youngest Stars', an article in the August 1967 *Scientific American*.

'Frontiers in Astronomy', a collection of readings from *Scientific American* edited by Owen Gingerich and published by W.H. Freeman and Co., is recommended as an overview of some of the more exciting topics in modern astronomy, including such recent discoveries as quasars and pulsars.

APPENDIX #1: UNIVERSAL EXPANSION AND UNIQUENESS

Suppose the expansion is such that the velocity of recession of any galaxy from some central point is given by the vector $\underline{V}$, related to the vector distance $\underline{r}$ of that galaxy from the central point according to the law

$$\underline{V} = H\underline{r} \quad (H = \text{constant})$$

Suppose we observe a particular galaxy: call it galaxy #1. Its velocity is given by

$$\underline{V}_1 = H\underline{r}_1$$

But we observe this galaxy from our vantage point in the Milky Way. Suppose that the Milky Way is at a distance $\underline{r}^*$ from the centre of the expansion. We are therefore moving with a velocity

$$\underline{V}^* = H\underline{r}^*$$

away from this centre. When we observe galaxy #1, the velocity we infer for it is its velocity relative to us, or

$$\begin{aligned} \underline{V}_{rel} = \underline{V}_1 - \underline{V}^*, &= H\underline{r}_1 - H\underline{r}^* \\ &= H(\underline{r}_1 - \underline{r}^*) \end{aligned}$$

But the vector in brackets is just the distance of galaxy #1 from the Milky Way. Thus, if we now observe galaxies ##2, 3, 4, etc. their velocities of recession with respect to us will appear to be proportional to their distances from us.

Similarly, if astronomers on a planet in galaxy #1 observe the Milky Way, and galaxies ##2,3,4 etc., they will observe velocities proportional to the distances of these other galaxies from them.

In an expansion where the velocity is linearly proportional to the distance from some point, <u>all</u> observers moving with objects taking part in the expansion (galaxies), will see the rest of the objects apparently expanding around them with velocities linearly proportional to distance from them. Thus no observer is particularly privileged, and none can determine the centre of the expansion.

This discussion neglects edge effects and observable effects of galaxy evolution. We must appeal to observation for the information that the properties of the known galaxies are statistically the same in all directions, so we do not seem to be near an edge in the Universe.