THE UNIVERSE FROM $<10^{-36}$ SECOND TO $>10^{30}$ YEARS* PART—1

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The boisterous progress in astronomy over the last twenty years has been apparent to any reader of the scientific press, or even the newspapers. Galaxies, quasars, black holes and the big bang have entered the general vocabulary, if not the common understanding. In this lecture I will first discuss galaxies and their constituent stars: how they form and evolve to their eventual fate. I shall then ask a similar question about the entire Universe: its beginnings, and its fate in the very long term. In particular, will it go on expanding for ever, or will it recollapse in a universal cataclysm after a finite time? To allay any suspense I will give the answer straightaway. I don't know. Nobody knows. But I shall try to explain why it isn't foolish or presumptuous to ask about the Universe's fate. We won't have to wait millions of years to find out. On the contrary, research programmes now in progress may give a reliable long term forecast within this decade.

STARS

Astronomers and cosmologists normally deal with things whose ages and evolution times are measured in billions of years. We understand quite well the life cycle of stars like the Sun. Such stars start their lives by condensing gravitationally from interstellar clouds. They then settle down on the so-called main sequence, their energy being derived from fusion of hydrogen into helium in their interiors. When hydrogen in the core is exhausted, such stars swell up to become red giants. They eventually settle down to a quiet demise as white dwarfs. Nuclear fusion, well understood in theory, provides enough power to keep the Sun shining for ten billion years. The solar system is four and a half billion years old, so there are five billion years to go before the Earth and the other inner planets are engulfed by the Sun's expansion to the size of a red giant.

Not everything in the cosmos happens on such a slow timescale. Some stars heavier than the Sun end their lives violently by exploding as supernovae. The best known instance of this is the Crab nebula, the expanding debris of a stellar explosion seen and recorded by Chinese astronomers in 1054 A.D. Supernova explosions signify the violent end-point of stellar evolution, when a star too massive to become a white dwarf exhausts its available nuclear energy. The star then faces an energy crisis; its core catastrophically implodes, and the outer layers are blown off. The centre of the star collapses to a dense 'cinder', a neutron star only about 10 km across. In such a star, material is squeezed to nuclear densities, $\sim 10^{14}$ times higher than the density of ordinary solids. The gravitational force on the surface of a neutron star is $10^{12}$ times higher than on the Earth, and one would need to fire a rocket at almost half the speed of light to escape from its surface gravitational pull. The neutron star in the Crab nebula is apparently pulsing about 30 times every second. It is believed that it is in fact rotating at this rate, and that strong magnetic fields produce a kind of lighthouse beam of radiation which passes through our line of sight once every revolution. Neutron stars exemplify supremely well the way in which the cosmos offers us a 'laboratory' where we can study how material behaves under conditions far more extreme than could be simulated on Earth.

The properties of stars could in fact have been deduced by a physicist who lived on a perpetu-
ally cloud-bound planet. He could have posed the question: 'Can one have a gravitationally confined fusion reactor, and what would it be like?' He could reason like this. Gravity is amazingly weak on an atomic scale. Its weakness is exemplified by the huge number relating the electrical and gravitational forces between electron and proton in a single hydrogen atom.

\[ N = e^2 / G m_e m_p \approx 10^{39} \]

But if enough atoms are piled together, gravity may become important because

\[ \text{[Gravitational binding energy per atom]} \]
\[ \propto M / R \propto M^{2/3} \] (for constant density).

Gravity becomes significant when the mass involved reaches

\[ M_* = N^{3/2} m_p \]

Gravitationally confined fusion reactors must be massive because gravity is weak. Eddington, in his classic book on the internal constitution of the stars\(^1\), was the first person to express this line of argument clearly. He showed that the general properties of stars could be predicted (though he did not know about fusion), by considering the effect of radiation pressure in their interiors. He then said, 'We draw aside the veil of cloud beneath which our physicist is working and let him look up at the sky. There he will find a thousand million globes of gas, nearly all with masses in this range — that is to say between a half and fifty times the Sun's mass'.

Supernovae may seem a long way away and a long time ago. But it is only by studying the births of stars, and the explosive way they die, that we can tackle such an everyday question as where the atoms we are made of came from. Complex chemical elements are built from hydrogen via the nuclear reactions that provide the power source in the cores of ordinary stars. The abundances of the elements are quite well known: they can be determined in the solar system by direct measurement, and inferred spectroscopically in stars and nebulae, and indeed in other galaxies. The relative abundances display many regularities. All the carbon, nitrogen, oxygen and iron on the Earth could have been manufactured in the stars which exhausted their fuel supply and exploded before the Sun formed. The solar system then condensed from gas contaminated by debris ejected from early generations of stars. There is now some quantitative understanding of these processes of cosmic nucleosynthesis, which can account for the relative abundances of different elements—why oxygen is common but gold and uranium are rare—and how they came to be in the solar system\(^2\). Biologists can trace our ancestry back to primitive protozoa, but the astronomer goes back further still. Each atom on Earth can be traced back to stars that died before the solar system formed. A carbon atom, forged in the core of a massive star and ejected when this explodes as a supernova, may spend hundreds of millions of years wandering in interstellar space. It then finds itself in a dense cloud which contracts into a new generation of stars. It may then be once again in a stellar interior, where it can be transmuted into still heavier elements. Alternatively it may find itself out on the boundary of a new solar system in a planet, and may be eventually in a human cell. We are literally made of the remains of long-dead stars. (The key pioneering concepts of stellar nucleosynthesis were developed by adherents of the steady state theory, whose tenets forced them to seek a present-day mechanism for forming the chemical elements. This body of work\(^3\) may be that cosmology's most valuable enduring legacy.)

Stars are so long-lived compared with astronomers that we only have, in effect, a single 'snapshot' of each one. But as compensation billions are available for study; and we can check our theories, just as you could infer the life cycle of a tree, even if you had never seen one before, by one day's observation of a forest. Of special interest are places like the Orion nebula, where even now stars are condensing out of glowing gas clouds; and star clusters, containing stars of different sizes which can be presumed to have formed at the same time.
GALAXIES

Let us now enlarge our horizons from the fate of individual stars, and consider the whole Universe of galaxies. It is more than four hundred years since Copernicus dethroned the Earth from its central cosmic position. In the 18th century, William Herschel suggested that the Milky Way might in fact be a flat disc of stars in which the Sun was embedded. But it was not until the 1920s that the Sun lost its central position within the stellar disc; and only then was it fully accepted that our Milky Way, our Galaxy, was just one fairly typical galaxy similar to thousands of others, and that galaxies are the basic units making up the large scale universe.

The light from most galaxies is essentially due to their stars and gas. Individual stars are too faint to be detected, but spectra can be taken of the integrated light from all the stars that make up a galaxy. Galaxies are held in equilibrium by a balance between the effects of gravity, which tends to make the stars to fall together, and the countervailing effect of the stellar motions, which if gravity did not act would make the galaxy fly apart. In some galaxies the stars move in nearly circular orbits in giant discs. In others, the less photogenic ellipticals, the stars are swarming around in more random directions, each feeling the gravitational pull of all the others.

A good deal is understood about the dynamics and stellar content of galaxies. But we are still flummoxed about the most basic question of all: why galaxies exist, why the most conspicuous large-scale entities in the cosmos should be stellar aggregates containing perhaps \(10^{11}\) stars with dimensions of \(\sim 10^4\) light years. There is no theory to explain this, at least no generally accepted theory.

There is however a widely adopted ‘scenario’ that accounts qualitatively for the two basic types of galaxies, discs and ellipticals. Let us suppose that all galaxies started their lives as turbulent gas clouds contracting under their own gravitation. The collapse of such a gas cloud is highly dissipative, in the sense that any two globsules of gas that collide will radiate their relative energy by producing shock waves, and will merge. The end result of the collapse of such a gas cloud, particularly if it is rotating will be the production of a rotating disc. This is the lowest energy state that such a cloud can reach if it loses energy but does not lose or redistribute its angular momentum. On the other hand, stars do not collide with each other, and cannot dissipate energy in the same fashion as gas clouds (see figure 1). This suggests that the rate of conversion of gas into stars is the crucial feature determining the type of galaxy that results. Elliptical galaxies will be those in which the conversion is fast, so that most of the stars have already formed before the gas has had time to settle down in a disc. Contrariwise, the disc galaxies will be those in which much of the star formation is delayed until the gas has already settled into a disc. According to this picture, ellipticals and spirals may have the same age. The disc galaxies

Figure 1. Schematic view of galaxy formation. Gas clouds merge and dissipate energy when they collide, but stars do not collide at all. The gas clouds (if they have a net angular momentum) settle into a rotating disc following collapse, whereas stars which condense out before the disc forms will retain orbits filling the entire original volume.
are those with slower metabolisms, cases of arrested development, which have not yet got so close to the final state in which essentially all the gas is tied up in low mass stars or dead stellar remnants.

The basic physics involved in normal galaxies is nothing more exotic or highbrow than Newtonian gravity and gas dynamics. If the cosmologists can give us some primordial fluctuations which condense into giant gas clouds, and if we can understand more about star formation, we should be able to understand the gross properties of present-day galaxies².

QUASARS AND ACTIVE GALACTIC NUCLEI

But another mystery lurks at the centres of some peculiar galaxies. These clearly involve something more violent than ordinary stars, and the disturbed appearance suggests some concentrated activity in the nucleus.

Astronomers have, over the last twenty years, discovered a whole zoo of objects in which the nucleus of the galaxy manifests violent activity, as though millions of supernovae have exploded in unison. Quasars are the most extreme instances. In the quasars, a small central nucleus seems to be outshining all the rest of the galaxy. One such quasar was observed in the autumn of 1975 to undergo an outburst in which its luminosity rose, within a single week, by an amount equivalent to turning on ten thousand galaxies like our own. Such an object must involve a power source far exceeding ordinary stars but concentrated in a region no larger than our Solar System. A consensus has emerged over the last few years that quasars, which obviously involve a large mass in a small space, probably result from a runaway process whereby gas and stars accumulate in the gravitational potential well at the centre of a galaxy, until some threshold is crossed where gravity overwhelms all other effects. This leads to a black hole, of millions (or even billions) of solar masses. Let me briefly recall what this concept connotes.

We can loosely define black holes as bodies that have collapsed to such small dimensions that no light nor any other signal can escape from them. They are expected in most theories of gravity; they are not merely consequences of Einstein's general relativity. Indeed they were in essence conjectured two hundred years ago on the basis of Newtonian gravity and the ballistic theory of light. John Michell, an under-appreciated polymath of 18th century science, wrote a paper in 1784 in which he noted that the escape velocity from the Sun was about one five hundredth that of light, and said. "If the semi-diameter of a sphere of the same density as the Sun were to exceed that of the Sun in the proportion of five hundred to one, and supposing light to be attracted by the same force in proportion to its vis inertiae with other bodies, all light emitted from such a body would be made to return towards it, by its own proper gravity". So Michell was suggesting, as did Laplace a decade later, that the most massive objects in the Universe might be undetectable by their direct radiation, but may still manifest gravitational effects on material near them.

Newtonian theory is inappropriate when gravity is very strong. The simplest treatment of a black hole within Einstein's theory was advanced by Karl Schwarzschild in 1916. He showed that a black hole has a certain characteristic radius, proportional to its mass, which is in fact just the same $2GM/c^2$, as Laplace and Michell estimated. This corresponds to the minimum radius from which light can escape to an external observer. The gravitational deflection of light is a very small effect in the solar system and in most astronomical contexts. But light is severely bent in the strongly curved space close to the schwarzschild radius. An experimenter situated just outside this radius would need to aim a beam of light almost directly outwards in order that it should not be dragged back and eventually swallowed by the black hole. If he ventured within the radius, he would be unable to send any-light signals to the external world. Although the region enclosed within the Schwarzschild horizon is shrouded from an external observer's view, a freely-falling experimental colleague, carrying a clock, could pass
Figure 2. Some features of a Schwarzschild black hole.

Inside without experiencing anything specially unusual as he went through the critical radius. But the experimenter would then have entered a region from which, however hard he accelerated, he could never escape. He would eventually reach the central singularity where tidal forces (the difference between the gravitational acceleration of his head and his feet) would become infinite. He would be crushed out of existence. He would reach this so-called singularity in a definite finite time as measured by his own clock. But an external observer would never see his experimental colleague fall within the Schwarzschild radius. A sphere of this radius acts rather like a one-way membrane. As it is approached, the falling experimenter’s clock would appear to the distant observer to run slower and slower. Any signal that he sent would become more and more redshifted, implying the experimenter would disappear and his signals fade. One cannot learn anything about the extreme conditions near the central singularity by sending an experimental colleague (who should be an expendable colleague). Such knowledge is reserved for those whose Faustian urge leads them across the horizon, despite the inevitable destruction that would ensue.

A strong motivation for interest in black holes is that they represent objects where gravity has overwhelmed all other forces, allowing one to test theories of gravitation under the most extreme conditions. But there are several other reasons for studying black holes. They interest the astrophysicist because they are in a sense the ‘ghosts’ of dead stars or galaxies. They are objects that have collapsed, cutting themselves off from the rest of the Universe, but leaving a gravitational imprint frozen in the space they have left. To the physicist, gravitational collapse is important because the central singularity must be a region where the laws of classical gravitation are transcended, and one needs some unified physical theory to understand what is going on. Black holes also have an important bearing on our general concept of space and time, because near them space behaves in peculiar and highly non-intuitive ways. For instance, time would ‘stand still’ for an observer who managed to hover or orbit just outside the horizon, and he could see the whole future of the external Universe in what to him seemed quite a short period. Even stranger and less predictable things might happen if one ventured inside the hole.

Some of us are becoming optimistic that quasars, hyperluminous power-sources in the middle of some galaxies, can be understood—that their central ‘prime mover’ involves a black hole as massive as a hundred million suns, fuelled by capturing gas (or even entire stars). This captured debris swirls downward into the potential well, moving nearly at the speed of light, being squeezed to high temperatures and radiating before it is swallowed. This hypothesis can explain not only the overall power but the detailed form in which the radiation emerges. A key result of general relativity is that where the black hole forms, it emits bursts of gravitational radiation and quickly settles down to a standardised stationary state characterised just by mass and spin, obeying equations discovered by Roy Kerr twenty years ago. This is colloquially known as the theorem that ‘black holes have no hair’. It is ironic that the astrophysical entity which is strangest to us is the one for which the theoretical description is most complete. Theorists hope that by studying the flow of gas and magnetic fields around a black hole they will be
able to understand the details of quasars, just as over the last fifty years they have come to understand what powers ordinary stars. At the same time, this work may offer a real test of Einstein’s gravitational theory, which predicts the exact form of black holes.

but from advances in instrumentation. Such a boost occurred when the photographic plate and spectrograph were introduced in the 19th century. And such has been the case as technical improvements have proceeded apace in recent times.

Bright and beautiful photographs of galaxies seen in popular books give a misleading impression. Galaxies are low surface brightness objects, barely detectable above the night sky, and only long exposures reveal them at all clearly. Our view of the extragalactic universe is still a sadly dim and blurred one.

Optical observations will always remain pivotal for studying ordinary stars or aggregates of stars. It is no accident that stars like the Sun mainly emit photons of a few eV energy, and that these are the ones our eyes respond to. Optical astronomy is in no way ‘passe’. Improvements in techniques, particularly in detector sensitivity, have been dramatic. There is a great contrast between the cold and lonely work of the traditional astronomer and the working environment of his modern counterpart at the console of a big telescope.

But visible light is only a narrow part of the electromagnetic spectrum. The radiation from more exotic objects—quasars and the other manifestations of those whirlpools around black holes in the centres of some galaxies—spills over into other wavebands. That is why newer techniques such as radio astronomy have been in the forefront of studies of violent events in the Universe.

Of equal importance has been the development of space research, enabling us to study types of radiation which do not penetrate through the atmosphere. Space astronomy began with pioneering efforts using sounding rockets, going up above the atmosphere to collect a few minutes data before coming down again. But only fifteen years later we have the Space Shuttle, and x-ray telescopes which represent an advance on the first sounding rockets equivalent to going from Galileo’s telescope to the 200” telescope. (X-rays are particularly important as a signature of high energies and temperatures.) In 1985 the Shuttle is
expected to launch the Space Telescope into orbit above the blurring and absorption caused by the atmosphere. This hundred-inch telescope will show details twenty times sharper than from the ground. It will be particularly useful in probing deep into space, and advancing our knowledge of cosmology.


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ANNOUNCEMENTS

NATIONAL SYMPOSIUM ON KINETICS AND MECHANISM OF REACTION IN SOLUTION

Under the auspices of the University Grants Commission, New Delhi and the University of Mysore, the Department of Post-graduate Studies and Research in Chemistry, University of Mysore, Mysore, is organising a National Symposium on Kinetics and Mechanism of reactions in solution for research workers in the Indian Universities and National Laboratories from 23–25 July 1983.

The Symposium consists of plenary and invited lectures and will have contributed papers. Special lectures setting the theme of the Symposium will be given by eminent scientists in India on the significance of the subject in research and technology.

The topics covered by the symposium are: (i) Oxidation reactions with aromatic sulphonyl haloamines, peroxydisulphate, peroxydiphosphate, cerium (IV), vanadium (V), manganese (III), N-Bromosuccinimide and other oxidants; (ii) Hydrolysis reactions, (iii) Substitution reactions, (iv) Thermal and Photochemical reactions (v) Exchange reactions and (vi) Polymerization reactions.

Papers for presentation at the Symposium along with a copy of the abstract not exceeding 100 words should reach Prof. D. S. Mahadevappa, Director, National Symposium on kinetics and Mechanism of reactions in solution, Department of Post-Graduate Studies and Research in Chemistry, Manasagangothri, Mysore 570 006, on or before 31st May 1983.

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"RASHTRA BHUSHAN"—FOUNDATION AWARD

Dr. Jayant Narlikar, the noted mathematician and a Fellow of the Indian Academy of Science, Bangalore, has been awarded the 1981 "Rashtra Bhushan" Foundation Award of Rs. One lakh, by the Fuel Instrumentry and Engineers Ltd., Ichalkaraji, Maharashtra (India).