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To:
That Indomitable Spirit within,
That inspires Our Search without,
Of the Universe,
and of the Self within. . .

Preface

The basic aim of fundamental physics and cosmology is to understand the nature and structure of the Universe and to decipher and comprehend the underlying laws that govern the Cosmos. This justifies current efforts to find a theory that will unify the forces of nature known today, namely the weak and strong nuclear forces, electromagnetism, and gravity. Although we seem to have at present a good theory that combines the first three forces, to unite it with gravity to generate a quantum gravity theory has been an unfulfilled dream and elusive goal for a long time now.

How are we to achieve this? As efforts are made to obtain evidence of quantum gravity, as has been done for the past several decades without success, my own feeling is that it may be worth considering phenomena in the Cosmos where these key forces come together to generate possibly observable effects. What we need are detectable and observable signatures of possible quantum gravity phenomena. These could give us the real clues leading to such a unified theory.

From such a perspective, we undertake here a journey into one of the most fascinating intellectual adventures of past decades, namely understanding the final fate of massive collapsing stars in the Universe, or in general the gravitational collapse of massive matter clouds on a larger scale. This is of great interest in fundamental physics and cosmology, for gravitation theory and modern astrophysical observations. This phenomenon could be intimately connected to our search for a unified understanding of basic forces of nature, namely gravity, which governs the cosmological universe, and the microscopic forces, which include the quantum phenomena.

Using Einstein's theory of gravity this investigation takes us to the world of black holes, spacetime singularities, and other intriguing possibilities. Today, this continues to be a crucially important, unresolved area in astrophysics and cosmology forming the foundation of modern black hole physics and its current applications. The issue is also relevant to mysterious, very high energy astrophysical phenomena observed in the Cosmos which defy any consistent theoretical understanding. They include, for example, cosmic gamma ray bursts, active galactic nuclei, quasars, and powerful jets from galaxies.

According to the general theory of relativity, a massive star that collapses catastrophically under its own gravity when it runs out of its internal nuclear fuel must give rise to a spacetime singularity. Such singularities are the regions in the Universe where physical quantities take extreme values and become arbitrarily large. The singularity might be hidden within a black hole or visible to faraway observers. Thus, general relativity predicts that a massive star's final fate of collapse is either as a black hole or as a visible naked singularity. In the latter case, ultra-high density and curvature regions formed during the gravitational collapse are visible from far away, and there can be rather intriguing observational consequences.

Within such a context, we discuss here recent results and developments on the gravitational collapse of massive stars and matter clouds. We suggest that a deeper understanding of catastrophic gravitational collapse, where energy scales grow extraordinarily high, can be a testing ground for examining, developing, and refining our efforts toward a unified quantum gravity theory. We indicate the exciting possibility that collapsing massive stars and the resulting spacetime singularities may provide a laboratory where one can test the unification possibilities for basic forces of nature.

In this way, the phenomenon of collapsing massive stars becomes all the more interesting and intriguing. Also, the possible connection to the very high energy cosmic phenomena mentioned earlier is worth exploring, and we consider possible observational and astrophysical implications when naked singularities form in the Universe.

The story that develops has amazing curves and ups and downs. In fact, black hole physics has undergone key changes in recent times. What began with the remarkable discovery by Chandrasekhar in the 1930s on white dwarf mass limits continued with detailed insights on neutron stars and pulsars, further moving onto dizzy domains of black holes and singularities. While this is all supposed to be scientific investigation and hard core fundamental physics, the emotional debates and controversies that have flared up from time to time during past decades have been no less spectacular.

While several interesting conclusions have emerged from these investigations in recent years, as we discuss here, the debate is far from over and this continues to be an area of great scientific excitement. Perhaps this proves again the vitality, importance, and key nature of the issues and themes involved.

It is my hope to show at the end of the discussion here that the emerging story is no less exciting and thought-provoking than Einstein gravity itself, from which it has developed. If the following narrative creates a few moments of happy and insightful thought, the effort here will have succeeded.

Pankaj S. Joshi
Mumbai, 2014

Acknowledgments

My thoughts on these cosmic themes evolved and developed over many years and I owe much to many colleagues who offered animated and extensive discussions on the issues covered here. While the opinions did not always converge and kept evolving, there was never a lack of interest and excitement due to the very basic nature of the inquiry at hand. In particular, I thank Indresh Dwivedi, Rituparno Goswami, Daniele Malafarina, Ken-ichi Nakao, and all my collaborators for extensive discussions and debates. Their thought-provoking questions and comments have been invaluable.

Conversations with Stephen Hawking, Roger Penrose, and Robert Geroch made me think deeply and intensely on these problems, and those with Peter Biermann, Ramesh Narayan and Kip Thorne motivated me to probe the possible observational consequences of gravitational collapse scenarios. With much fondness I also mention here my few interactions with S. Chandrasekhar, who showed keen interest in these problems, and offered his critical comments. His penetrating insight inspired me to tackle the complex problem of gravitational collapse in Einstein's theory of gravity.

I express my sincere gratitude to Jayant Narlikar, P. C. Vaidya, and A. K. Raychaudhuri, who always took a keen interest in the progress of our work over many years, and offered many useful comments. The very kind support to our work from M. G. K. Menon and B. V. Sreekantan has been invaluable, and I thank them warmly.

My detailed discussions with George Musser, Vithal Nadkarni, and Bharat Kapadia on black holes and cosmology brought out the rich tapestry of interwoven ideas and different aspects of the problem, and I extend many thanks to them. The discussions with Adlung Sonke at OUP led to the idea of this book, and I am very grateful to him for his careful attention throughout. Jessica White, Ania Wronski, Charles Lauder, Ralph Footring, and Gandhimathi Ganesan have taken much care to see this work comes out well, and I am very thankful to them.

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Our Universe

Man's journey in search of the fundamental laws that govern the Universe has led us to some of the most fascinating insights on the nature and structure of the Cosmos. Even the smallest child begins observing the Universe as soon as she arrives on Earth, and such observation sparks curiosity and leads to questions about the Universe. The inquiry gradually matures to intuitive, logical, and mathematical thinking and analysis of the Cosmos' basic nature and structure. This is the start of our understanding of the Universe, leading to a wide variety of new discoveries and inventions.

Early astronomers were amazed to learn that the Universe and phenomena such as the occurrence of day and night, eclipses, ocean tides, and the motions of planets, stars, and other heavenly bodies were not arbitrary or random but followed specific patterns and fundamental rules. Such an appreciation prompted an inquiry into the basic laws governing these phenomena and a search for more of an understanding of the world around us.

In due course, this led us to the body of knowledge that we today call science. The quest has resulted in an impressive understanding of the Universe and its basic happenings. This includes Einstein's theory of relativity, and quantum theory, which governs the tiny constituents of matter. Today we have very large telescopes on Earth and in the skies which probe the deepest recesses of the Cosmos. At the same time we build mammoth accelerator machines that collide the tiniest of particles of matter at the fastest velocities possible. While the frontiers of knowledge keep expanding, superb applications have frequently resulted from the basic laws of nature that we have discovered, which have made human life smoother and healthier.

Microcosm, Macrocosm, and Forces of Nature

We observe the Universe today in its smallest dimensions of atoms and hadrons constituting the same in large particle colliders, while at the largest cosmic scales we can see galaxies and their clusters millions of kilometers away amidst a vast expanse. On the one hand, tiny subatomic particles travel close to the speed of light and collide to create a plethora of new basic particles. On the other hand, faraway galaxies collide and merge to give rise to new cosmic entities, while cosmic structures constantly form and disperse. Our knowledge and conception of the Cosmos evolve as our search progresses (see Fig. 1.1 for a historical perspective on the Universe around us).

Such observations of the Universe and the mathematical calculations have shown that all these phenomena are governed by certain basic laws and forces in nature. While day-to-day happenings in nature at our own scales seem to be governed mainly by electric and magnetic forces, at the scale of the atoms and elementary particles so-called weak and strong nuclear forces govern key outcomes. When we move onto the larger cosmic scales, it is fairly clear that more than any other force, it is the force of gravity that counts and decides the natural phenomena, such as the formation of galaxies and stars and the clustering of matter on very large scales.

While different forces seem to rule different arenas and scales in the Universe, man, however, has a passion to search for a certain unity amidst all the diverse phenomena that surround us. We would like to obtain a single logical structure that describes and explains nature in its entirety. If possible we would also like to predict the Cosmos and its happenings using such a framework.

In fact the word ‘physics’ comes from the Greek root ‘physis’, which means the basic element or key principle of nature. For example, while electricity and magnetism were observed as a collection of different and diverse natural phenomena, it was James Clerk Maxwell’s theory from the nineteenth century that gave a unified description of these phenomena in a single logical framework with a system of mathematical equations. Similarly, while the happenings within the atom and its nucleus are now known to be governed by weak and strong nuclear forces, contemporary, grand unified theories combine these forces with the electromagnetic phenomena and again provide a unified description of these happenings. On the other hand, when we move to the larger

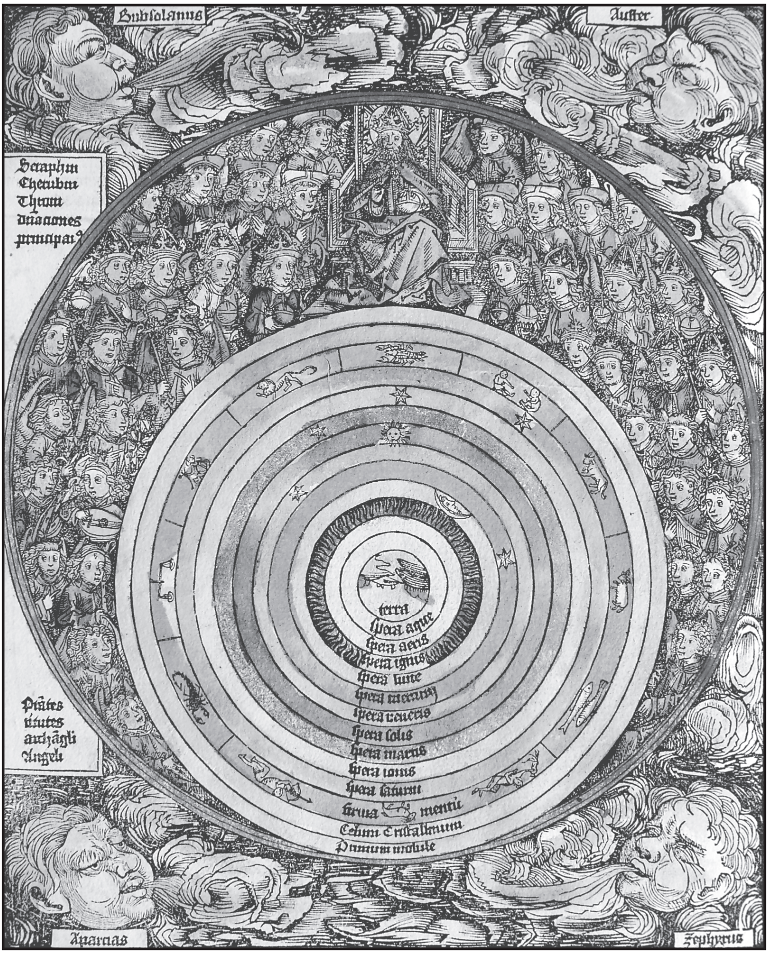

Figure 1.1 An ancient view of the Universe. While mankind is located at the center of the Universe, with the celestial sphere and the dome of sky up above, outside that lie various unknown forces and powerful entities, probably those of air and water and fire and others.

scales of space and time, namely planets, the solar system, and beyond to the expanse of stars and galaxies, it has been known for a long time that it is the force of gravity that governs the dynamics of these objects.

Explaining and predicting planetary motion due to the law of gravity has been the greatest success of Newtonian mechanics. However, Newtonian gravity requires an infinite speed for the propagation of the force of gravity. This is not consistent with the special theory of relativity as derived by Albert Einstein in 1905, where no speed greater than that of light is possible. A new theory of gravity was therefore inevitable, which came in the form of the general theory of relativity formulated in 1915. General relativity, or the Einstein gravity, has been the most successful theory of gravity, having passed several experimental and observational tests and providing many new exciting predictions about the Universe.

Despite these successes, it must be admitted that a vast ocean of ignorance lies before us. Current cosmology tries to understand how the Universe came into being, how galaxy formation was triggered, and how the intricate cosmic web of galaxy clusters observable today through gigantic telescopes came into being. Among others, the formidable problems of the missing or dark matter and the unseen or dark energy that drives the accelerated expansion recently observed in the Universe are far from being well understood. At the microscopic level, as we continue in our quest for the basic building blocks of matter, and for the key forces that govern them, newer and finer layers of reality emerge and open up before us.

Nevertheless, such an entirety of unfolding phenomena has not discouraged us from our search. In fact, to meet such a daunting challenge, mankind has embarked on even bigger and ever more ambitious missions to probe and understand the Cosmos, in both its microcosmic and macrocosmic realms. This is what has led to space telescopes that see the farthest reaches of the Universe, and to the most powerful of particle accelerators that probe the deep secrets of the tiniest constituents of matter.

Thus, while we have been sharpening our technical instruments for observing the Universe, we also have come to realize that intuition and the mind, which are our very basic tools for understanding the Universe, need to be refined and sharpened and understood better. An opinion has emerged that without understanding the nature of the mind, a better understanding of the Universe may not be possible (see Fig. 1.2).

Needless to say, such a journey into the Cosmos has led us to some fascinating landscapes that we had never imagined possible. Many of the phenomena in nature certainly defy our basic and gut feelings about the Universe and always surprise us. As we journey through

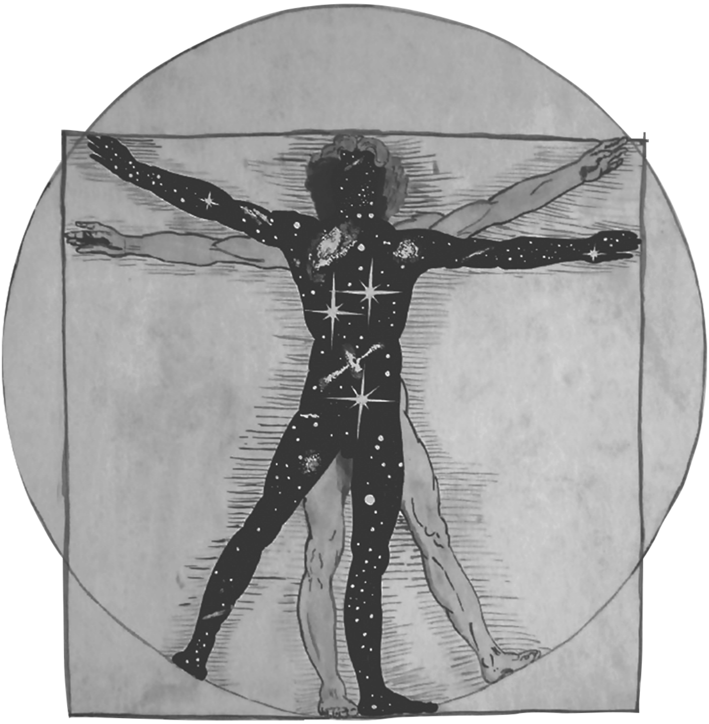

Figure 1.2 The modern approach to the Cosmos sometimes prefers to see man and the Universe as an integrated whole. While we would like to understand our relation to the Universe in its entirety, the big mystery is: Can the human mind really grasp the Universe? Whether it is conceptual frameworks and theory or mathematical calculations and series of experiments, in the end it is the human mind that must make sense of all that experience in the form of coherent laws of nature. These laws may explain existing phenomena, and also make new predictions about nature.

the frontier of knowledge, new domains of the unknown keep opening, and perhaps such a scenario is always bound to arise.

The Role of Gravity

Gravity is the force that man has experienced and tried to understand for ages. Clearly, it governs the Universe on the large scale that we see, perceive, and experience. In the past, we observed planetary motion, ocean tides, eclipses, and so on as manifestations of the force of gravity. Today, we now in addition observe the motion and dynamics of stars and galaxies, the powerful jets from active galactic nuclei, pulsars and quasars, powerful gamma ray bursts, and other such phenomena that occur in the skies.

In addition, there are now the intricate and intriguing concepts and theories of black holes and spacetime singularities, time warps and changing spacetime topologies, and so on. All these together make an amazing spectrum of phenomena that gravity creates in the Cosmos. Many new facets of gravity physics have opened up in recent decades, going further than Newtonian dynamics, and are based largely on Einstein's theory of general relativity. We will describe later in some detail the remarkable picture and various perspectives that have emerged about the Universe that involve gravity in a fundamental way.

Two major revolutions that took place about a century ago in our understanding of the Universe were relativity theory and quantum theory. While the former dominates mainly at the very large scales of the Universe and in very strong gravity fields, the latter has given us a fairly good idea about the microscopic world of elementary particles and their interactions in nature. Of course, the goal has been a unified understanding of both these domains by obtaining a quantum gravity theory, but that dream is still far from being realized. To that end we need new theoretical insights and advances, and more observational data about the Universe.

Our knowledge and conception of the observable Universe are reaching a most interesting and crucial turning point. On the one hand, we are probing the deepest recesses of matter by means of particle collider experiments with the highest collision energies. This has revealed new information about the world of tiny particles and about the fields that cause these interactions. On the other hand, we are facing increasing limitations to Earth-bound experiments, and formidable difficulties arise when we try to understand these phenomena theoretically, due to the complexity of the dynamics involved.

A possible solution may be that if we observe the Cosmos more intensely and carefully, we may come across many more phenomena where the basic forces of nature may be operating collectively in unison. Such observations and signatures could give us crucial inputs for our search for a unified theory of nature. In this sense, astrophysical and astronomical observations are crucial for moving towards a deeper understanding of the Universe. At present, although we have a wealth of observations coming in, major challenges to fundamental physics and cosmology still remain unresolved.

In regard to the force of gravity, whenever physicists deal with very strong gravity fields, such as in the late stages of massive collapsing stars, a huge quantity of matter compacted in a small region such as the center of a galaxy, or rapidly spinning neutron stars, they must use the general theory of relativity to properly understand such phenomena.

Einstein's theory of gravity is very rich, both conceptually and mathematically, and must be handled with very careful analysis and understanding. When applied appropriately to understanding physical scenarios such as those above, it produces rather intricate and intriguing consequences, such as the formation of spacetime singularities, black holes and time warps, and highly curved geometries which may have remarkable observational consequences.

In such a context, the theory and observations of massive collapsing stars may hold a basic key to the understanding of gravity. Such a collapse necessarily gives rise to spacetime singularities, as predicted by general relativity. We point out that if such singularities are visible to observers far away in the Universe, they would then provide a wealth of information about quantum gravity processes occurring in very strong gravity fields which develop in such regions. Such naked singularities developing in the gravitational collapse of massive stars could be viewed as providing us with laboratories of very high energy that would be unreachable at terrestrial levels.

As for Einstein's theory of gravity, despite its remarkable features, we face many key problems. One issue has been that general relativity is a geometric theory of gravity with a mathematical structure very different from other theories of physics, such as Newtonian mechanics or quantum theory. Therefore it has not been possible so far to obtain a unified description of the laws of nature for all four fundamental forces that we mentioned earlier. This has been recognized as one of the most important and outstanding problems in modern physics today, namely how to unify gravity with quantum mechanics. Efforts over the past decades to obtain a unified theory of quantum gravity have included string theories and loop quantum gravity.

As discussed here, rather than only going after purely theoretical frameworks and attempts, which has been the case so far, it may be beneficial and rewarding to look for phenomena in the Universe where quantum effects and gravity come together. In such scenarios, it may be possible to observe genuine quantum gravity effects. This could give us a much better handle to understanding quantum gravity theory and its real workings and basic framework.

The point is, in the terrestrial experiments and many of the observations of the Universe so far, gravity has been a rather weak force. So it stays apart and disconnected from rest of the basic forces in nature and in particular quantum effects. However, as we shall argue, the gravitational collapse of massive stars and the resulting spacetime singularities may be the natural phenomena where quantum and gravity come together to operate in unison. The observations of such regions in the Universe could provide us with the crucial missing steps which we need for a unified theory. This would be an important transition from general relativity, which is a purely classical theory without any consideration of quantum mechanics.

Dynamical Evolution in the Universe

One of the key tasks for any physical theory is to describe and predict the dynamical evolution of physical systems and the evolving phenomena in the Universe. This could be at either a local or global level. For cosmic systems, which are mainly governed by gravity, this is to be accomplished using Einstein's theory of general relativity (see Fig. 1.3).

Such phenomena, on very large scales, include the expansion of the Universe as a whole, driven by gravity, the formation of galaxies and clusters of galaxies, and other such large-scale structure formations. On a somewhat smaller scale, there are formation processes that initiate the life of a newborn star, and later the gravitational collapse of these stars when they run out of their internal nuclear fuel. Thus we could be working on very large scales of the Universe as a whole, or on relatively smaller scales of stars and galaxies, where gravity essentially governs the dynamical processes and evolution of these systems.

As has been observed in the Cosmos today using gigantic telescopes either on Earth or in space, there is a continual dynamical change essentially governed by gravity. Thus, at the largest scales, galaxies recede from each other, or they can sometimes collide and merge together. Then mammoth huge clouds of interstellar matter come together in a slow gravitational collapse and trigger the formation of galaxies or clusters. This can also make even larger filaments and voids in the Universe.

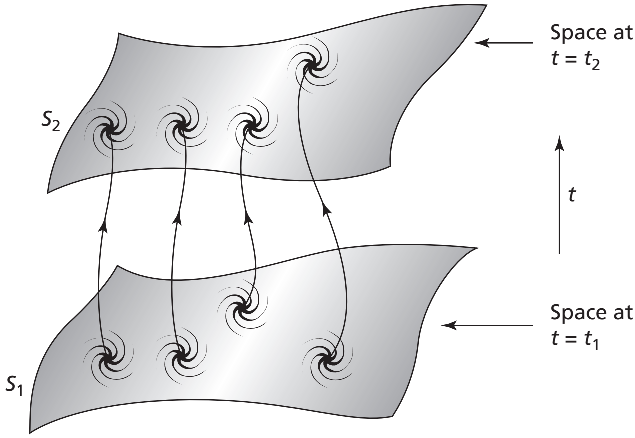

Figure 1.3 In Einstein's gravity theory, we would like to trace the dynamical evolution of three-dimensional space as time moves forward. The evolution of such a system, for example that of a cluster of galaxies, is governed by Einstein's equations. The locations of these galaxies and their distances from each other change over time. Here S_1 and S_2 denote three-dimensional spaces (shown in two dimensions), and the former evolves into the latter as time moves forward from t_1 to t_2, as given by the field equations of gravity. Similarly, we could work out the evolution of the system in the past.

On a smaller scale, gravitational collapse can trigger star formation, where a local cloud of matter contracts under its own gravity, heats up enormously to cause nuclear burning within, and thus first a proto-star and then a star is born. Such star formation goes on in various regions in the Universe all the time, and so does the gravitational collapse of stars toward the end of their life-cycles.

In those cases where the system is very large and gravity is very weak, a Newtonian approximation may work, but essentially it is Einstein's equations of general relativity that govern these phenomena. So one needs to build mathematical models, using Einstein's equations, to describe these phenomena. Such solutions could be obtained either through fully analytic techniques or through numerical models calculated with computers. In either case, the basic idea is to describe and model these gravitational processes, understand their evolution in the Universe, and as a result be able to make predictions.

As indicated earlier, it is not always easy to predict the dynamical evolution of physical systems such as stars, galaxies, or the Universe as a whole under the force of gravity within the framework of Einstein's theory of gravity. There are difficulties and complexities due to the non-linear nature of gravity and to inevitable global aspects related to the spacetime continuum that we must deal with. Also, non-trivial topologies for the Universe could arise with involved geometries giving rise to otherwise unanticipated features. We must, however, look around the mathematical as well as the physical landscape and try to proceed by finding smarter ways for creating new insights into these most interesting cosmic phenomena of nature.

In our present discussion, we will be mainly interested in tracing the dynamical evolution of massive stars within the framework of Einstein's theory of gravity. A massive star, when it runs out of internal nuclear fuel toward the end of its life-cycle, undergoes a continual gravitational collapse. General relativity predicts that a spacetime singularity must arise as a result. Thus, a super-ultra-dense region in spacetime forms. Such a singularity either is wrapped within a black hole or is a visible naked singularity. It is only through tracing the dynamical evolution of the massive matter cloud using Einstein's equations that the final fate of such a star can be determined. We shall discuss these issues in detail in later chapters.

Black Holes, Singularities, and Quantum Gravity

A wide variety of phenomena are created by the all-pervasive force of gravity in the Cosmos. It is therefore not surprising that the modern science of gravitation and cosmology has introduced us to many of the strangest ideas about the Universe. One of the most extraordinary and unexpected is the ultimate fate of a massive star that has reached the end of its life-cycle. A star derives its energy from the nuclear reaction burning within and having exhausted the internal fuel that has sustained it for millions of years as it shined and gave out heat and light, the star is no longer able to hold itself up under its own weight and the force of self-gravity. It starts collapsing, shrinking catastrophically in a matter of seconds. Modest stars like the Sun also collapse toward the end of their lives, but they then stabilize later at a smaller size of about a thousand kilometers. The resulting stable configurations are called white dwarfs. However, if a star has tens of times the mass of the Sun, its gravity then overwhelms all the forces of nature that might possibly halt its gravitational collapse.