Kitty Ferguson

‘Captivating and enthralling’
The Washington Times

Prisons of Light: Black Holes

About the Book

What is a black hole? Could we survive a visit to one? Perhaps even venture inside? What would we find? Have we yet discovered any real black holes?

And what do black holes teach us about what physicist John Archibald Wheeler called “the deep, happy, mysteries of the universe”?

These are just a few of the tantalizing questions examined in this jargon-free review of one of the most fascinating topics in modern science. In search of the answers, we trace a star from its birth to its death throes, take a fabulous hypothetical journey to the border of a black hole and beyond, spend time with some of the world’s leading theoretical physicists and observational astronomers scanning the cosmos for evidence of real black holes, and take a whimsical look at some of the wild ideas black holes have inspired.

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To Colin and Duff

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Prologue

For many hundreds of thousands of years, we who live on the earth have watched the night sky, awed by its beauty and mystery, longing to understand what we see . . . and to see more. For most of that time we had only our eyes, our imaginations, and our mathematics to help us, until in 1609 the first telescopes appeared and opened up vast new possibilities. Over the next three hundred years we improved our telescopes dramatically and formed the impression, coming entirely from visible light, of an elegant universe, predictable and patterned, not changing discernably over millions or even billions of years.

There was much we were missing.

The earth's atmosphere is a barrier. By the 1930s we were able to use radio receivers to discover things that aren't visible with any optical telescope, but we were still like crabs scuttling on the ocean floor, wondering what we would find if we stuck our heads above the surface of the water. So we proceeded to put X-ray detectors first on rockets and, in the 1970s, in orbit beyond our atmosphere and found much more in the heavens than anyone could see on a clear night with the most powerful earthbound telescope.

With radio and X-ray telescopes and later with infrared and gamma-ray telescopes, we've discovered that the universe is not, after all, the serene universe we thought we knew early in the twentieth century. It's much more violent and complex, less easy to predict, with stars ripping hot gas from their neighbours, beams of radiation sweeping around from swiftly rotating pulsars, cataclysmic explosions in the cores of galaxies, quasars changing in brightness over very short periods of time, and jets of gas spewing out over tremendous reaches of space from the nuclei of galaxies and quasars.

In the second decade of the twenty-first century we see far more than our predecessors did a mere eighty years ago, but even with powerful telescopes probing the universe in every part of the spectrum from the earth’s surface, from orbit, and from space probes, we still don’t see everything we know is out there.

No one has seen a black hole, nor, it seems, will anyone ever see one. Until the late 1980s no one could even claim to have found conclusive indirect evidence of a black hole. However, with the eyes not of telescopes but of physics theory and mathematics we have been scrutinizing these amazing phenomena for a long time.

The idea that there might be ‘dark stars’ with gravitational attraction so powerful that all their light is pulled back in is not a product of twentieth-century science. It came from the British natural philosopher John Michell in 1783, about a hundred years after Isaac Newton introduced his theories of gravity. That is not to suggest that scientists have been thinking about the notion for two hundred years. On the contrary, the idea languished in almost total obscurity from about twenty-five years after its introduction until the second decade of the twentieth century, when Albert Einstein gave us a deeper understanding of gravity and theorist Karl Schwarzschild became curious about how a star’s gravity, in Einstein’s new way of thinking about it, might affect its light.

By the mid-1980s the theory of black holes was highly respected and meticulously developed physics theory. It was taught in most graduate schools. Confidence ran high that black holes exist. There were several good black hole ‘candidates’. But unequivocal evidence of a black hole continued to elude astronomers. Now, a few short years later, we do have convincing observational evidence of the presence of several black holes and good reason to conclude there are many more. The evidence is indirect evidence – circumstantial evidence it would be called in a court of law. No telescope has shown us a picture of a black hole. Discovering a promising candidate and demonstrating that this candidate actually *is* a black hole requires an ingenious collaboration of theory and observational astronomy. Nevertheless, in the case for and against black holes, the jury has returned a verdict. These unlikely, fantastic creatures do exist. We have indeed discovered several.

Does the black hole saga end here? Shall we tuck it away in the history books, enshrine it in permanent science museum exhibits, turn our attention to other matters? The theorists, the observational astronomers, and the popular media are satisfied . . . and that's it? No. We've only begun to find out what black holes are like and what roles they play in the real universe, and we do not yet understand what happens at their centres. Hidden within black holes are clues to what physicist John A. Wheeler calls the 'deep, happy mysteries' of the universe. The attempt to unlock these mysteries is the great adventure of modern science. Black holes don't give up their secrets easily. Finding real black holes hasn't allowed us to probe inside them. We may never be able to do that.

What are these inscrutable, invisible objects? Where do they come from? What is the source of their incredible power? What makes us so certain they are there, if we can't ever actually see them?

1
A cosmic case of burnout

The Great Nebula in Orion, a region of star formation, is visible to the naked eye as the 'star' in the 'sword' of the constellation Orion. (National Optical Astronomy Observatories.)

It is therefore possible that the greatest luminous bodies in the universe are on this very account invisible.
Pierre-Simon Laplace, 1795

GAZING AT THE night sky may indeed give us the impression that stars are eternal and unchanging. They are not. A star is born and shines for millions, perhaps even billions of years, and then it stops shining. Less massive stars like our own sun burn longer than more massive stars. The lifetime of the sun is likely to be ten to twelve billion years in all. But no star shines forever.

A black hole is one of the ways a star may spend its old age, one possible ‘final state’ of a star. Though not every star ends up as a black hole, and not every black hole began as a star; nevertheless, if you want to understand black holes, you need to know something about stars.

Figure 1.1 is an overview of the life of a star like the sun, a story that begins in the cloud of gas at the left centre of the picture and ends with the thin line trailing off on the right. This particular star doesn’t become a black hole. The artist has drawn the thin line to indicate that it spends its old age as a ‘white dwarf’. If it were a black hole, we would see nothing at all trailing off on the right. It may reassure the faint-hearted to know that according to our best knowledge about stars and black holes the sun will never become a black hole. We’ll learn why in the pages that follow. However, the mass of the sun is important in the study of black holes because it has become the standard of measurement when we talk about how massive a star or a black hole is. If you read about a black hole of ‘one hundred solar masses’, that means its mass is one hundred times the mass of the sun. For those whose memories are vague when it comes to the meaning of ‘mass’, there will be a briefing in a moment.

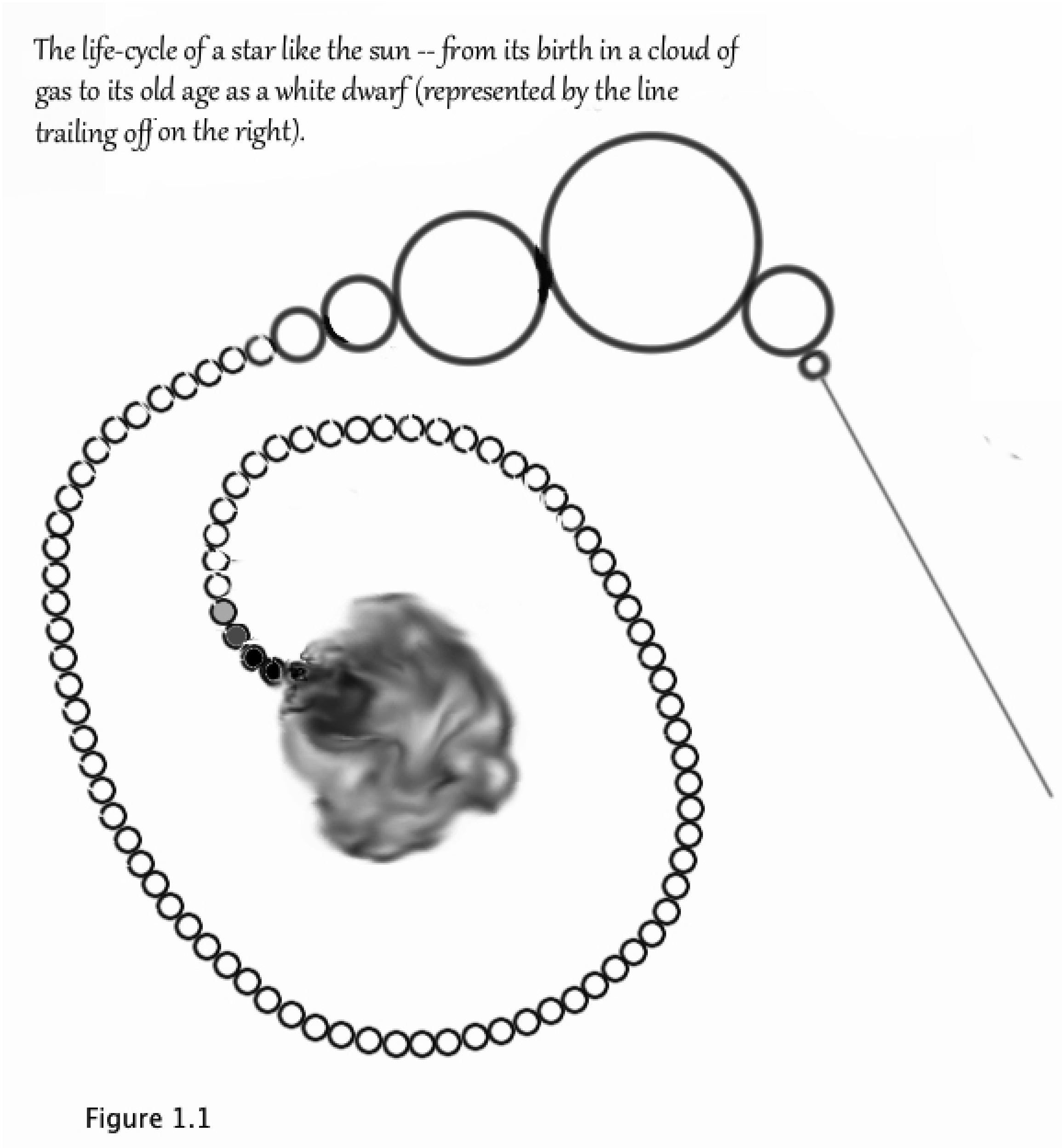


Figure 1.1.

Enormous clouds of gases out in space, like the one represented in the life-cycle drawing, are the nurseries of stars. Those of us who prefer to take nothing as a given may wonder why we should begin the story there rather than ask where the cloud of gas came from – a question that currently occupies some of the foremost minds in physics and astrophysics. There have been theories and discoveries that show hope of unravelling the mystery of why gas or anything else has bunched together in one area rather than remaining evenly dispersed throughout the universe. Most promising, in the spring of 1992, George Smoot of the University of California at Berkeley and colleagues discovered wrinkles in the cosmic background radiation originating in the early universe, wrinkles that were an early indication of such unevenness. The subject is, regrettably, outside the scope of this book. We must begin our story in an era when we know matter *has* accumulated because we have observed it.

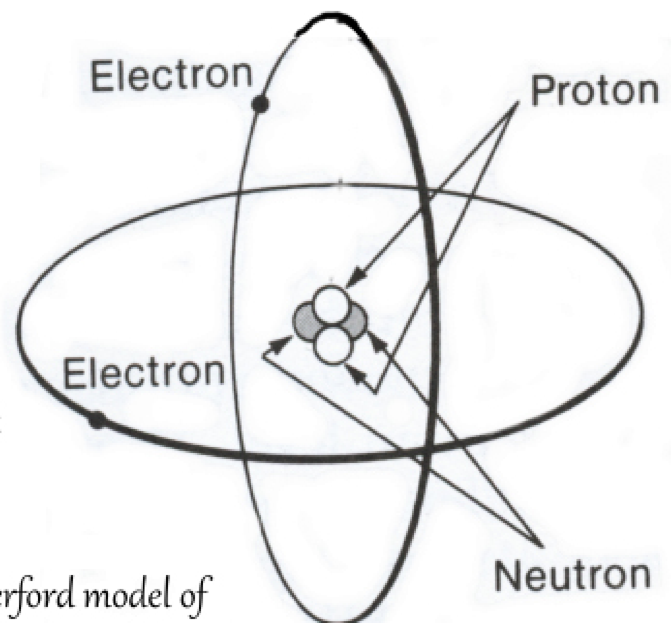
A good example of an accumulation of gas is in the magnificently photogenic Great Nebula in Orion (Chapter 1 frontispiece). The gas there is mostly hydrogen. Hydrogen gas, like all other ordinary matter in the universe, consists of atoms. Atoms in turn are composed of elementary particles and a comparatively enormous amount of empty space. The familiar schoolbook drawing of an atom (Figure 1.2*a*) shows a nucleus in the centre made up of particles known as protons and neutrons, with other particles called electrons orbiting the nucleus. That's the way Ernest Rutherford drew the atom in the early part of the twentieth century. In order to understand some parts of this book, it will be necessary to relinquish that familiar picture and replace it with something less easy to draw or comprehend, more like the drawing in Figure 1.2*b*, but neither drawing is adequate when it comes to scale. We'll be closer to the correct scale if we imagine the nucleus being about the size of a city block and the electrons orbiting or swarming in a cloud in an area about the size of the earth. Also, neither drawing even begins to indicate how much empty space is in an atom, and this empty space plays a key role in the fate of a star.

The Rutherford model of a helium atom

Protons (with positive electrical charge) and neutrons (with no electrical charge) cluster together at the centre of the atom, in the nucleus.

Electrons (with negative electrical charge) can't be in the nucleus, but they are attracted to protons and tend to stay nearby.

Notice that there is a lot of empty space in an atom much more actually than this drawing suggests, because even at this magnification the electrons and the nucleus are so small that you really couldn't see them at all.



In this model -- the Rutherford model of a helium atom -- the electrons orbit the nucleus the way planets orbit the sun. We now know that because of the uncertainty principle of quantum mechanics, electron orbits are not really well-defined paths as shown in this model.

Figure 1.2 (a)

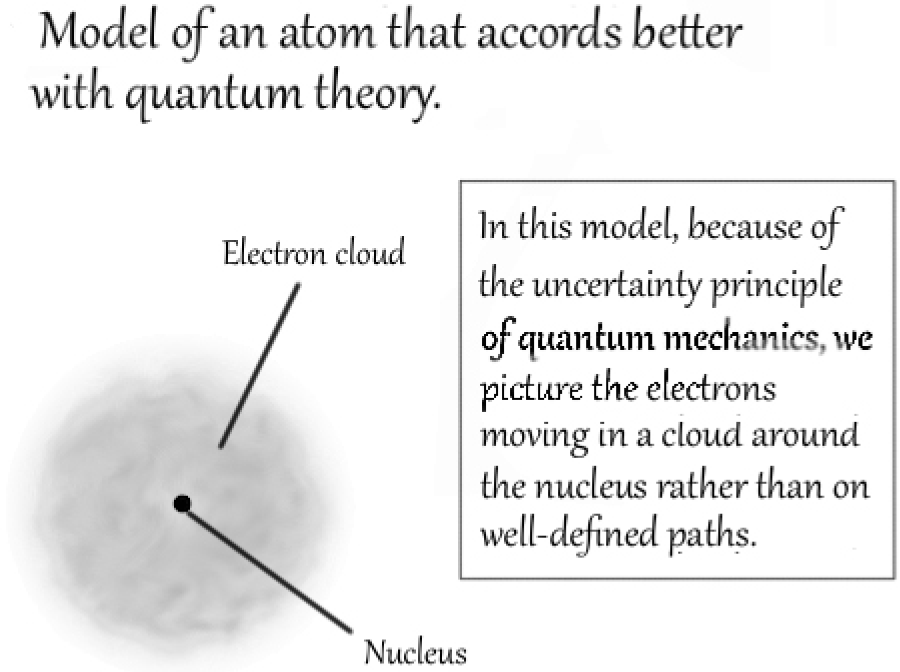


Figure 1.2(b)

Figure 1.2. Models of the atom.

In an area such as the Orion Nebula, the atoms and particles have come near enough to one another in a gas to begin pulling on one another and drawing closer together still. We call this pull ‘gravity’, or gravitational attraction, something we take for granted as the force that keeps us from falling off the earth. We think less often of it working among the tiniest particles and among all the enormous objects out in space. Much of this book will be about the way gravity operates. We begin simply by noting that, other things remaining equal, the nearer objects approach one another the stronger the gravitational attraction between or among them becomes. In the hydrogen gas we’ve been talking about, the atoms respond to the pull of one another’s gravity and draw closer yet, moving faster because of the stronger gravitational attraction. Collisions occur more and more often and at higher speeds.

Everything heats up. When things have become sufficiently hot, the atoms in the gas stop bouncing off one another. Instead, the hydrogen nuclei begin to merge into one another and change into helium. This is the process called nuclear fusion (Figure 1.3). Because of the overcrowded conditions among the atoms in certain parts of the cloud of hydrogen gas, there will be a lot of it going on. It's like a controlled hydrogen bomb explosion, and the heat is indeed intense. We're no longer looking merely at a cloud of gas. Some of the gas has pulled itself together to form a star. The release of heat, as hydrogen nuclei continue to fuse, makes the star shine.

An example of nuclear fusion: A deuterium ('heavy hydrogen') nucleus, which contains one neutron and one proton, and a hydrogen nucleus, which consists of a single proton, get fused together to create a helium-3 nucleus, which contains two protons and one neutron. This is one of the fusion reactions that power the sun and other stars.

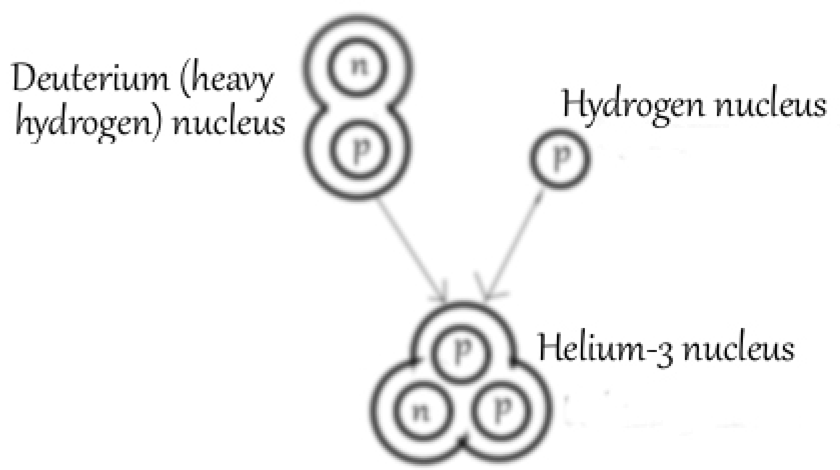


Figure 1.3

Figure 1.3.

Stars spend most of their adult years converting hydrogen to helium, and that's what keeps them alive. For all those millenia there is a balance – a tug-of-war, if you will – between two closely matched opposing teams. On the one hand there is gravity, the force that continues to draw the atoms and particles closer together. Left unopposed, gravity would cause the star to collapse in on itself. We who depend on a star for our continued existence are fortunate that gravity does not go unopposed. Paradoxically, gravity brings about nuclear fusion and thus assures that there IS an opposing team. The heat released in the nuclear reactions (as hydrogen becomes helium) creates enough pressure in the gas to balance the gravitational attraction, and the star doesn't collapse. Think of the way the pressure in a balloon holds the walls of the balloon apart. The rubber walls pull toward each other, trying to come together – which they will do quite readily if we let the gas out of the balloon. The pressure in a star doesn't allow it to collapse – which it would do quite readily if the nuclear reactions stopped occurring and gravity were allowed to have its way. The heat released in nuclear reactions also makes up for the heat lost as the star radiates light into space.

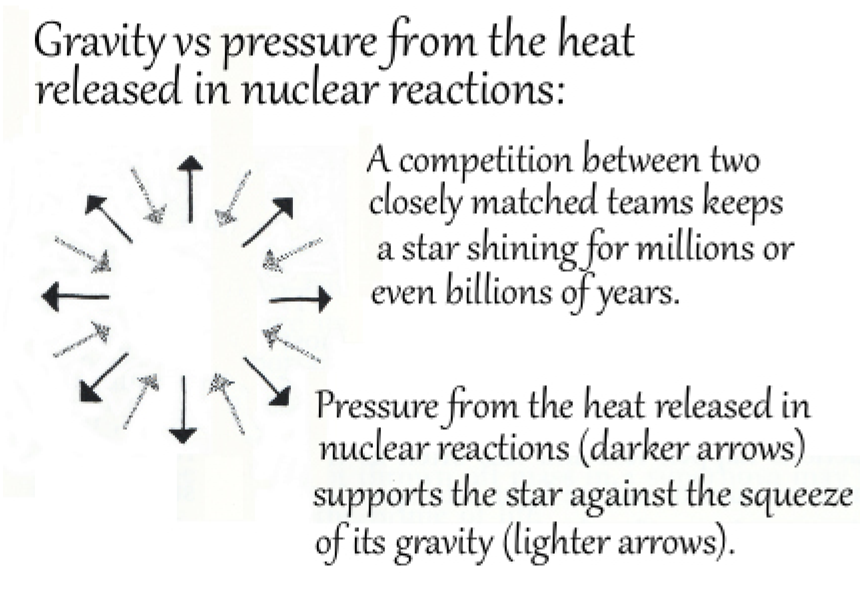


Figure 1.4

Figure 1.4.

Picture this tug-of-war, then (Figure 1.4). Pressure from the heat released in nuclear reactions is one team, gravity the other. Occasionally gravity appears to be winning. When the accumulation of helium ash snuffs out the central furnace of the star, the core begins to collapse, but the collapse itself soon produces higher temperatures and the star reignites, now fusing helium into carbon atoms and swelling into a red giant. In the life-cycle drawing in Figure 1.1 we see that happen. Were the star in the drawing our sun, in the red giant stage it might engulf the earth. In some stars the snuffing out and reignition occur several times, with stars fusing atoms into heavier and heavier elements.

This competition eventually ends with gravity the victor. When most of the hydrogen atoms have fused into helium atoms and some of those into carbon atoms and, in more massive stars, into heavier elements, the star finally exhausts its usable fuel. Nuclear reactions happen less and less often as the fuel runs out, but the star continues to radiate light into space even when it is no longer able to make up for the heat lost in this radiation. There is less and less heat and pressure to counteract gravitational attraction. After patiently holding its own for millions or billions of years, gravity wins the tug-of-war. The cooling star begins to shrink and collapse in on itself.

A very massive star during these last stages may blaze into a giant Type II Supernova, shining for a few weeks as brightly as ten million suns. While its centre collapses and crunches down to the density of an enormous atomic nucleus, its outside rips apart and becomes a glowing, expanding shell of gas. In the explosion the star throws off some of its matter, sometimes a very large portion of it, thus reducing its mass before continuing to collapse. How great a mass it ends up with after the explosion will be instrumental in deciding its fate.

It would perhaps be prudent to digress for a moment and clear up any confusion about the meaning of ‘mass’. We should not confuse mass with size. A small object can be ‘massive’. Within the earth’s gravity, we translate that to mean that a small object can be heavy, which is obviously true. A popular children’s book about black holes[1] makes the point with an illustration showing a mother and child watching a see-saw. At one end of the see-saw is a stack of elephants, each elephant standing on the back of the one below, stretching up out of sight at the top of the page. At the other end of the see-saw is a tiny pebble. We can tell from the way the see-saw is tilted that the pebble is outweighing the tower of elephants. Elementary school children learn that mass is a measure of how much matter (or how many particles of matter) is in an object, regardless of how loosely or densely that matter is packed. In the see-saw drawing, we know the pebble must consist of many more particles of matter than the tower of elephants does. The particles of matter in the pebble are much more densely packed. A more sophisticated definition of mass is that mass has to do with how much an object resists any attempt to change its speed or direction, but for our immediate purposes the important thing to understand is that as a star shrinks and becomes smaller it does not necessarily become less massive. An aged, drastically shrunken star that has not thrown off mass in a supernova may be as massive as it was in the prime of life.

Three possible fates now await a collapsing star.

1. It may settle down and spend its old age as a 'white dwarf' like the star in the life-cycle diagram, with a radius of a few thousand miles, not too much smaller than the earth but with a density of hundreds of tons per cubic inch. We observe many white dwarfs in our own part of the Milky Way galaxy. There is one orbiting Sirius (the Dog Star), the brightest star in our night sky (Figure 1.5). As we've said, the sun will probably end up as a white dwarf.
2. It may not settle as a white dwarf but instead crunch down until its circumference is approximately a mere 100 kilometres, ending up as a 'neutron star' with an incredible density of millions of tons per cubic inch. 'Pulsars', which we shall encounter later in this book, are neutron stars.
3. It may continue to collapse and form a 'black hole'.

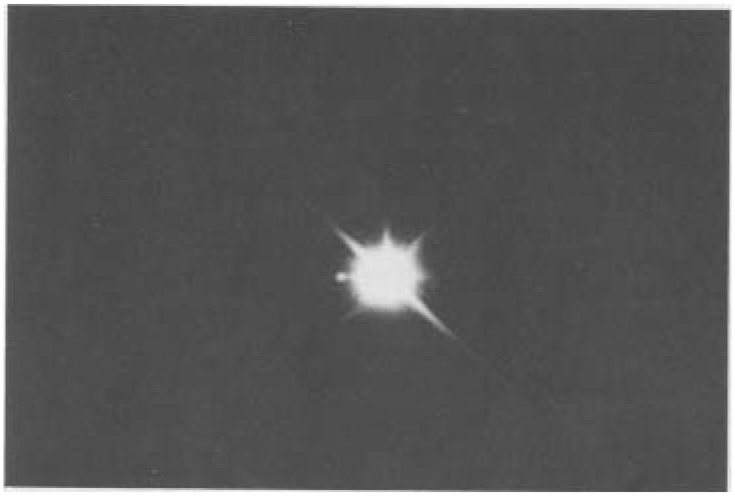


Figure 1.5. Sirius B, a white dwarf seen here as a small dot of light, orbits Sirius A, the Dog Star, the brightest star in our night sky. The spikes in the picture aren't real: they are caused by the support struts of the telescope. (Lick Observatory Photo/Image.)

Which will it be? What causes some stars to retire as white dwarfs, while others collapse to neutron stars and still others are doomed to crunch all the way down to black holes?

After all the fuel for nuclear reactions has been used up, gravity meets a fresh opponent – the 'exclusion principle'. All particles of ordinary matter – the particles that make up atoms, which in turn make up such things as this book, you and I, stars, gases – obey this principle. The exclusion principle insures that particles keep their distance and there will be empty space in atoms. Without it we would have no stars, or people, or any other of the familiar objects in our universe. We would have something more like a dense soup.

The exclusion principle requires that no more than two electrons can occupy the same region of space at the same time. Electrons – moving in clouds around the nuclei of atoms – are paired together in cells (or 'orbitals'). Electrons protest their confinement in these cells by moving erratically, shaking, flying around, kicking forcefully against adjacent electrons. This motion is called 'degenerate motion', and the pressure it produces is 'electron degeneracy pressure'. This pressure keeps electrons from being pulled into the nucleus of the atom.

As a star collapses, the clouds of electrons around the nuclei of the atoms in the star get squashed until the electrons are confined in cells many times smaller than they usually could move around in. In this situation an electron begins to behave in part like a wave. That may seem unlikely, but I will ask you to accept it for now and look forward to an explanation later. It stands to reason that the length of the wave cannot be larger than the cell the electron is in. Shorter wavelengths mean higher energy. Higher energy implies more rapid motion. It follows that the denser the matter in the star becomes, the smaller the cells will be; the smaller the cells, the shorter the electrons' wavelengths must be; the shorter the wavelengths, the higher the electrons' energy; the higher the energy, the faster the electrons' motion; the faster this motion, the larger the electron degeneracy pressure it produces. It is this pressure that will continue to support the star against gravity.

This scheme sounds as though it would continue to work in a highly satisfactory manner. As the pull of gravity increased, so would the pressure opposing it. There is, however, a hitch. Our universe has a speed limit which for all practical purposes seems to be unbreakable. That speed limit is the speed of light, approximately 300,000 kilometres (or 186,000 miles) per second. Degenerate electrons can't move faster than the speed of light. But even short of that, when matter is so dense that degenerate electrons move at *near* the speed of light, matter has serious difficulty supporting itself against the squeeze of gravity. Can it succeed?

In the late 1920s Subrahmanyan Chandrasekhar, a young Indian physicist then at the University of Cambridge, calculated that if a star's mass is less than 1.4 times the mass of our sun, gravity will not be able to overpower this exclusion principle repulsion among the electrons. The star shrinks and becomes a white dwarf, but, because of the exclusion principle, it shrinks no further. That star will not become a black hole. We now call this mass of 1.4 solar masses the 'Chandrasekhar limit'. Only in a star whose mass is *more* than the Chandrasekhar limit will gravity overcome the exclusion principle among the electrons and be the victor in this second competition (Figure 1.6).

Let's suppose now that we are dealing with a slightly more massive star, more than 1.4 solar masses. Is every star with a mass over the Chandrasekhar limit destined to be a black hole?

The Russian scientist Lev Davidovich Landau, who arrived at a limit similar to Chandrasekhar's, also called attention to another possible final state for a star. When gravity has overpowered the exclusion principle repulsion among the electrons, as the star squashes down, electrons are squeezed into the atomic nuclei and combine with protons in the nuclei to form additional neutrons. After a while the core of the star is almost entirely made of neutrons. Neutrons must obey the exclusion principle as surely as electrons must. The resistance to squeezing, partly due to degeneracy pressure and partly due to another force called the strong nuclear force, is stronger than it was previously among the electrons, presenting gravity with an even more formidable opponent. There is a complicating factor here, and no one is quite sure how important it might turn out to be. It's possible that the electrons in the crunch won't combine with protons but will instead turn into other particles which *can't* combine with protons, leaving plenty of protons hanging around among the neutrons. A mixture of protons and neutrons is easier to compress and the star is more likely to form a black hole. Nevertheless, the current consensus is that the maximum allowed mass for a ‘neutron star’ lies between 1.5 and 3 solar masses and is most likely to be about 3 solar masses. A neutron star is smaller and denser than a white dwarf.

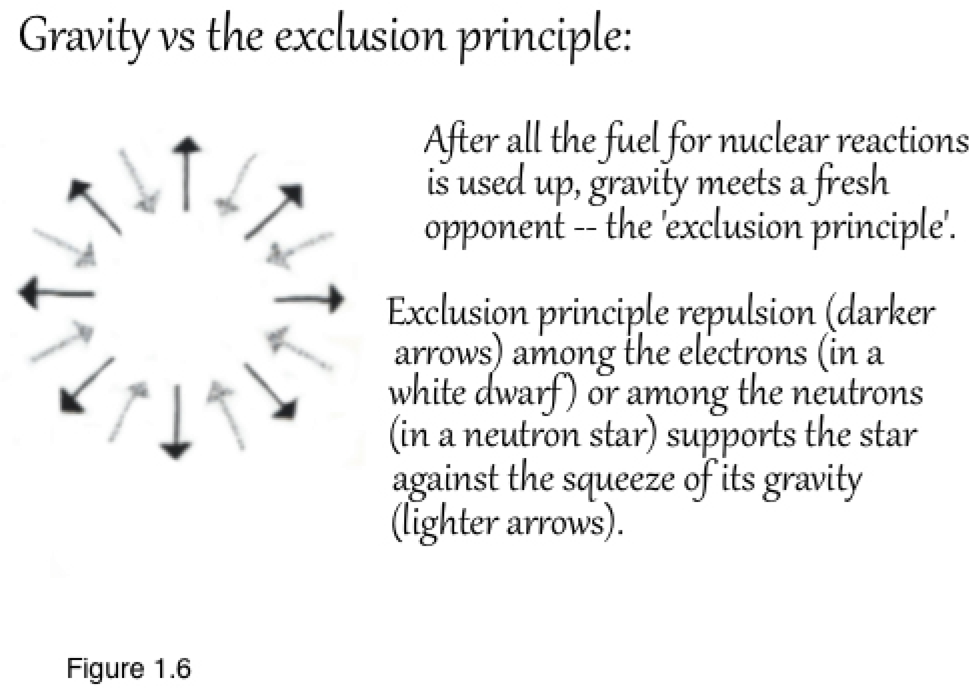


Figure 1.6.

However, suppose we have a star a little more massive than the maximum allowed mass for neutron stars. Is *that* star destined to become a black hole? Not necessarily. A star may lose a considerable amount of mass in a late-in-life explosion. However, if it doesn’t lose enough to bring it below the maximum allowed mass for neutron stars, about 3 solar masses, gravity *will* overpower both the exclusion principle repulsion among the neutrons and the strong nuclear force, and the star will continue to collapse. When it has reached a size not much smaller than it would have been had it remained a neutron star, the star will form a black hole.

Common sense suggests that there is something suspicious about this description. Why should it be the *more* massive stars that end up smallest, as black holes, and *less* massive stars that end up larger, as white dwarfs or neutron stars? Shouldn't it be the other way around? That question gives us a good excuse for a closer look at gravity.

Physicist John A. Wheeler of Princeton and the University of Texas asks us to think of gravity as a universal democratic system, with every particle in the universe casting a vote that can affect every other particle in the universe. Though no particle of matter has much gravitational influence by itself, when particles join forces and vote as a bloc (the earth, for instance, or a star), that bloc can wield enormous influence. The combined votes of all the particles in this great hulk of a planet under our feet obviously constitute a significant amount of gravitational clout.

We've said that mass is a measure of how much matter is in an object, how many matter particles have banded together to form this particular voting bloc. The greater the number of votes in the voting bloc, the greater the mass, and the greater the influence of that voting bloc. Getting back to the stars whose life stories we have been tracing – it should be clear that saying one star is more massive than another means that there are more particles of matter in it. The more particles of matter, the more gravitational attraction. Hence, the more massive the star, the more powerful the gravity team is in the tug-of-war, the more powerful the potential 'squeeze', and the more likely it is that the squeeze will be able to overpower the exclusion principle.

Gravity was the force that gave birth to the star in a cloud of gas. It was the force that kept the star in balance for all those years, not allowing it to fly apart but also contributing to the processes that prevented its collapse. Now, after millions or even billions of years have passed, gravity is the force that claims the star as its victim, squeezing all its enormous mass to something the size of the sun . . . then to the size of the earth . . . to the size of the moon . . . to the size of London . . . St. James Park . . . the lake in the park . . . a duck on the lake . . . a tennis ball . . . a marble . . . the head of a pin . . . the point of a pin . . . a microbe . . . For a star ending up more massive than about 3 solar masses, we know of no power capable of halting this catastrophic collapse. The star continues to crunch down even after it has become a black hole. It's best to think of a black hole *not* as a star, but as what happens to spacetime around a star that goes on collapsing to near infinite density.

1. Franklyn Mansfield Branley and Marc Simont, *Journey into a Black Hole* (New York: Harper Collins, 1988)