ISAAC ASIMOV

How we found out about

Black Holes

HOW WE FOUND OUT ABOUT

BLACK HOLES

Isaac Asimov

Contents

1. White dwarfs

In 1844 a German astronomer, Friedrich Wilhelm Bessel, discovered a star he couldn't see.

This is how it happened.

All the stars we see in the sky are moving about. They are so far away from us, though, that the motion seems very slow indeed. Only by making careful measurements through a telescope will the motion show up as very tiny changes in position.

Even using a telescope won't help much. Only the nearest stars show visible changes in position. The dim, distant stars are so far away that they don't seem to move at all.

One of the stars nearest to us is Sirius. It is about 80 million millions of kilometres away, but that is close for a star. It is the brightest star in the sky, partly because it is so close, and its motion can be measured easily through a telescope.

Bessel wanted to study that motion carefully, because as the Earth goes around the Sun, we keep seeing the stars

from slightly different angles. Instead of seeing a star move in a straight line, we see it move in a line that wiggles slightly because of the Earth's motion. The nearer the star, the larger the wiggle. From the size of the wiggle, if it is carefully measured, the distance of a star can be calculated. Bessel was particularly interested in this. In fact, he was the first astronomer ever to calculate the distance of a star. He did that in 1838.

He then became interested in measuring the wiggle in Sirius's motion. As he measured the position of Sirius night after night for a long time, he found that there was more of a wiggle to its motion than he had expected. It changed position because the Earth was revolving around the Sun, but there was another change in position too—a slower one that had nothing to do with the Earth.

Bessel concentrated on this new movement and found that Sirius was moving in an orbit around something or other, just the way the Earth moves in an orbit around the Sun. He calculated that it would take Sirius 50 years to complete its orbit.

But what caused Sirius to move in this orbit?

The Earth moves about the Sun because it is held by the Sun's powerful gravitational pull. Sirius must be held in a powerful gravitational pull of some sort too.

Sirius, however, is a star that has two and a half times the mass of our Sun. (*Mass* is the amount of matter something contains.)

From the way in which Sirius was moving, it had to be feeling the gravitational pull of a body that was large enough to be a star also. In other words, Sirius and a companion star had to be circling each other. We might call Sirius, "Sirius A", and its companion star, "Sirius B".

From the way in which Sirius A was moving, its compa-

nion star, Sirius B, had to be about as massive as our Sun.

Yet Bessel couldn't see Sirius B. It had to be there, for the gravitational pull had to come from something. Bessel decided, therefore, that Sirius B was a star that had burnt to a cinder. It no longer shone and therefore could not be seen. He called it the *dark companion* of Sirius.

Later on, he noticed that the star Procyon moved in such a way that it must also have a dark companion, "Procyon B".

Bessel had discovered *two* stars he couldn't see.

In 1862 an American telescope maker, Alvan Graham Clark, was making a lens for a new telescope. Such a lens must be polished perfectly so that stars can be seen sharply through it.

When he was finished, he tested the lens by looking through it at the star Sirius to see if it would show up as a sharp point of light.

When he did so, he was surprised to find that there was a dim spark of light near Sirius. If this was a star, it was not on any of the star maps that he had. Maybe it was the result of a flaw in the polishing of the lens.

No matter how carefully he continued to polish the lens, though, that spark of light did not go away. There was no similar spark when he looked at any other bright star.

Finally, Clark noticed that the spark of light was in just the position that Sirius's dark companion ought to be, and he knew he was looking at it. Sirius B was not a completely dead star after all. It still shone, but with only $\frac{1}{10000}$ the light of Sirius A.

In 1895 a German-American astronomer, John Martin Schaeberle, noticed a dim spark of light near Procyon. It was Procyon B, and it wasn't completely dead either.

By Schaeberle's time, though, astronomers had learned more about stars.
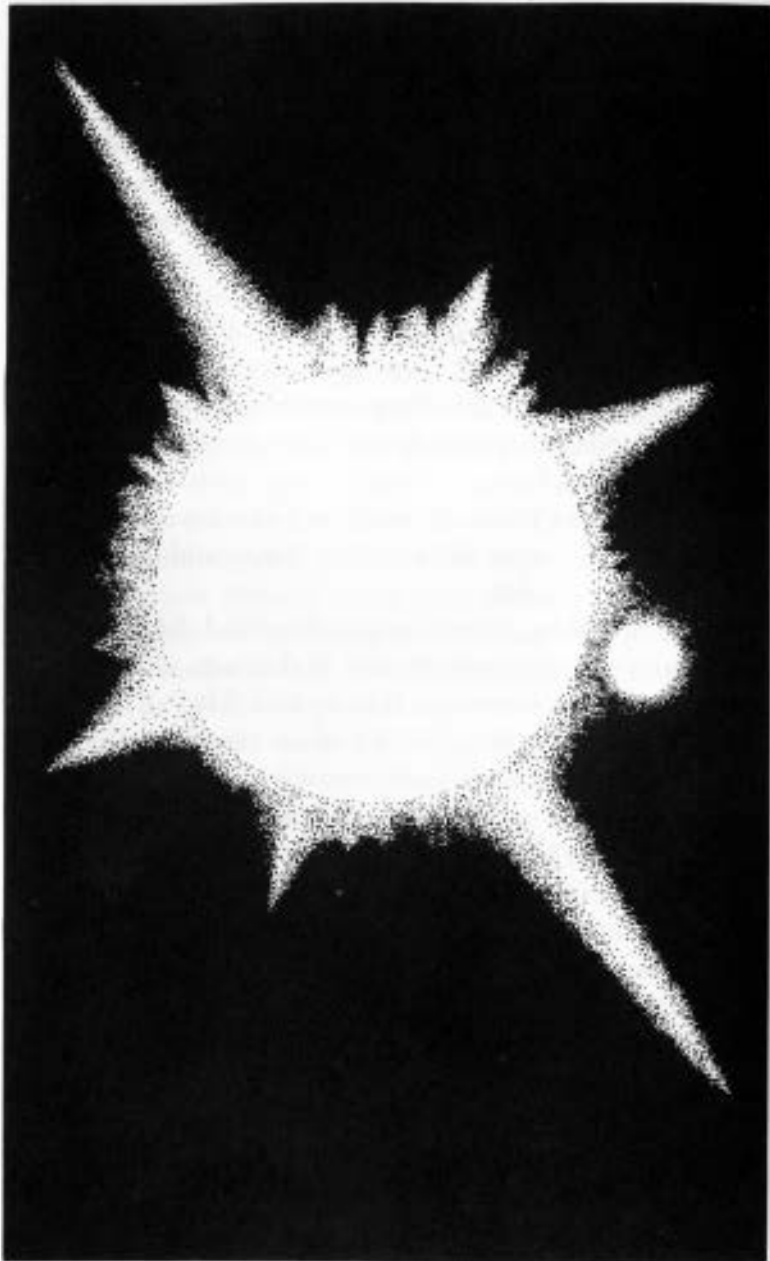
Light consists of tiny waves of different lengths, and astronomers had learned to separate starlight into a spread of these different wavelengths. Such a spread is called a *spectrum*.

In 1893 a German scientist, Wilhelm Wien, showed how a spectrum changed with the temperature of the source of the light. He showed, for instance, that if a star was on its way to flickering out, it would turn reddish it cooled down. If Sirius B was a dying star, it ought to be red—but it wasn't. Sirius B had a white light.

In order to check further on this, the spectrum of Sirius B had to be studied carefully. Sirius B was very dim, however, and was so close to the very bright Sirius A that it was hard to catch the little star's light and spread it out into a spectrum.

In 1915, however, the American astronomer Walter Sydney Adams managed to get the spectrum of Sirius B. He found that Sirius B had a surface temperature of 8,000°C. It was hotter than our Sun, which has a surface temperature of only 6,000°C.

If a star like our Sun was at the distance of Sirius B, it would shine like a bright star. It would not be as bright as Sirius A, but it would be quite bright just the same. Since Sirius B is even hotter than our Sun, it should shine at that distance even more brightly than the Sun—yet it does not. Sirius B shines with only ¼ the brightness that our Sun would show if it was at that the same distance.

How is that possible?

It must be that although the surface of Sirius B gleams brightly, there is very little of that surface. Sirius B must be a *tiny star*.

To be as dim as it is, despite its temperature, Sirius B must be only 11,000 kilometres across—no bigger than a large planet. It would take 86 stars the size of Sirius B,

placed side by side, to stretch across the width of our Sun. Because Sirius B is white hot and yet is so small, it is called a *white dwarf*. Procyon B is also a white dwarf.

White dwarfs are now thought to be quite common. Astronomers think that one star out of every 40 is a white dwarf. White dwarfs are so small and dim, however, that we can only see those few that are nearest to us.

Although Sirius B is so small, it still has a mass equal to that of our Sun, or it wouldn't be able to swing Sirius A about as it does.

If you were to take the mass of our Sun and squeeze it into a body no larger than Sirius B, the density would be very high indeed. (The *density* of an object tells us how much mass is squeezed into a particular volume.)

A cubic centimetre of the material of Sirius B, if it was brought to Earth, would weigh 2,900,000 grammes. That means Sirius B has a density of 2,900,000 grammes per cubic centimetre. The average density of the Earth is only 5.5 grammes per cubic centimetre. The material out of which Sirius B is made is more than 530,000 times as dense as the material of which the Earth is made.

This is astonishing. Solid matter on the Earth is made up of atoms that are touching each other. In the 1800s scientists thought that atoms were hard and solid little balls and that you couldn't push them any closer together once they were touching. If that were so, the density of material on Earth would be just about as dense as anything could be.

However, in 1911, the New Zealand-born scientist Ernest Rutherford showed that atoms were not hard, solid objects. The only hard, solid part of an atom was a tiny *nucleus* (the plural is *nuclei*). The nucleus is so tiny that it would take 100,000 nuclei placed side by side and touching to stretch across the width of a single atom.

Helium atom structure

Electron

Neutron

Proton
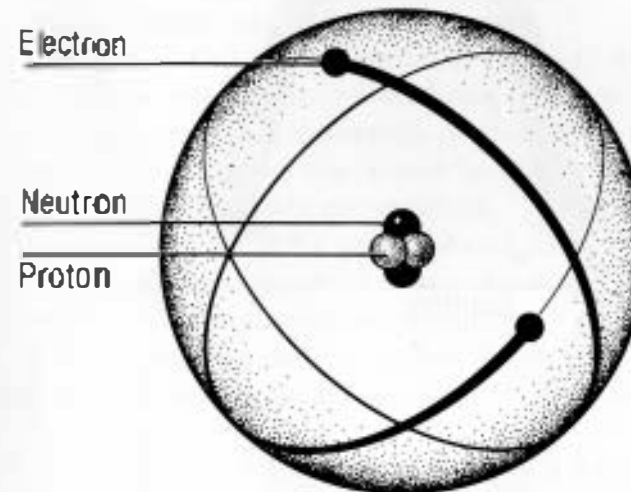
Hydrogen fusing to form helium

Hydrogen nucleus

Proton   Neutron

Helium nucleus
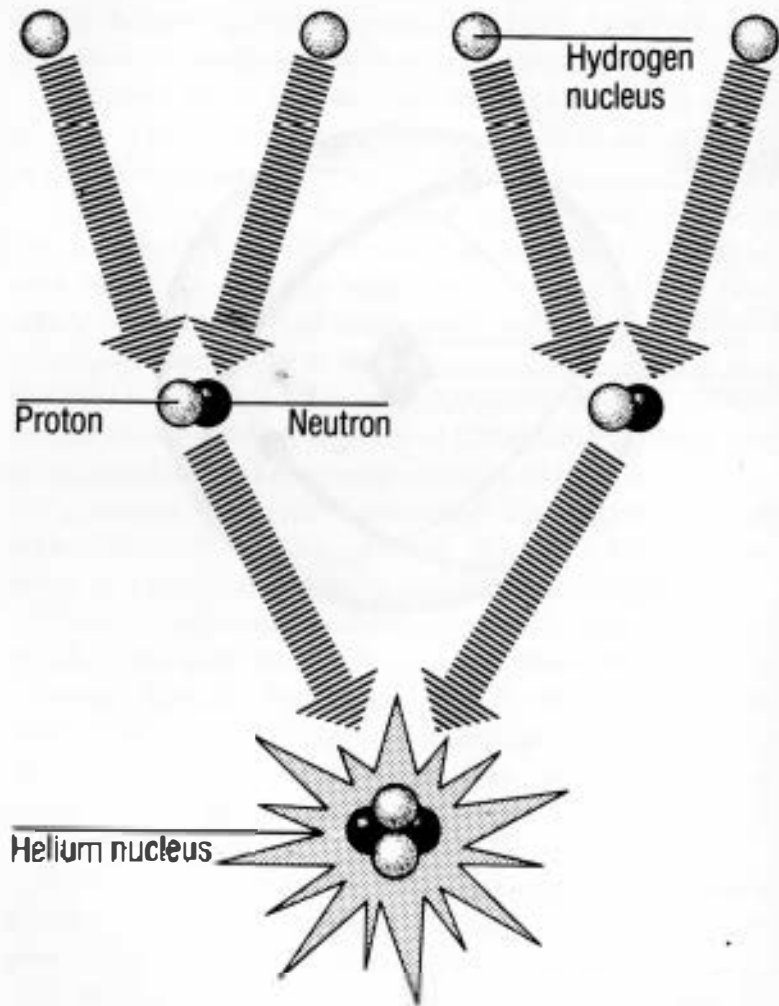
Despite its tiny size, the nucleus contains just about all the mass of an atom.

Around each nucleus are one or more *electrons* which have very little mass. The electrons are arranged in layers about the nucleus called *electron shells*.

When two atoms meet, the outermost electron shell of one makes contact with the outermost electron shell of the other. The electron shells are like bumpers that keep the atoms from getting any closer together.

On the Earth the gravitational pull isn't great enough to smash those electron-shell bumpers. Even at the core of the Earth, with thousands of kilometres of rock and metal weighing on the atoms in the very centre, the electron shells do not get smashed.

It is different in the case of a star like our Sun that is hundreds of thousands of times as massive as the Earth and has a gravitational pull that is much stronger. Atoms at the centre of a star have smashed electron shells. The electrons then move about loosely and do not surround the nuclei.

As a result, the nuclei can move about freely. They can even bump together and stick, thus undergoing changes that produce energy. So much energy is produced that the centre of a star can have a temperature of several million degrees. Some of that heat leaks out of the surface of the star in all directions, and that is why the star shines as it does. The heat developed in this way keeps the star expanded and doesn't let the atoms smash except at the very centre.

The energy at the centre of a star comes from the changeover of hydrogen nuclei (the smallest there are) to helium nuclei (the next smallest). Eventually, though, most of the hydrogen in the star is used up.

But by that time the centre has become so hot that the

1 Formation of the Sun

3 Red giant

4 White dwarf

2 The Sun at present
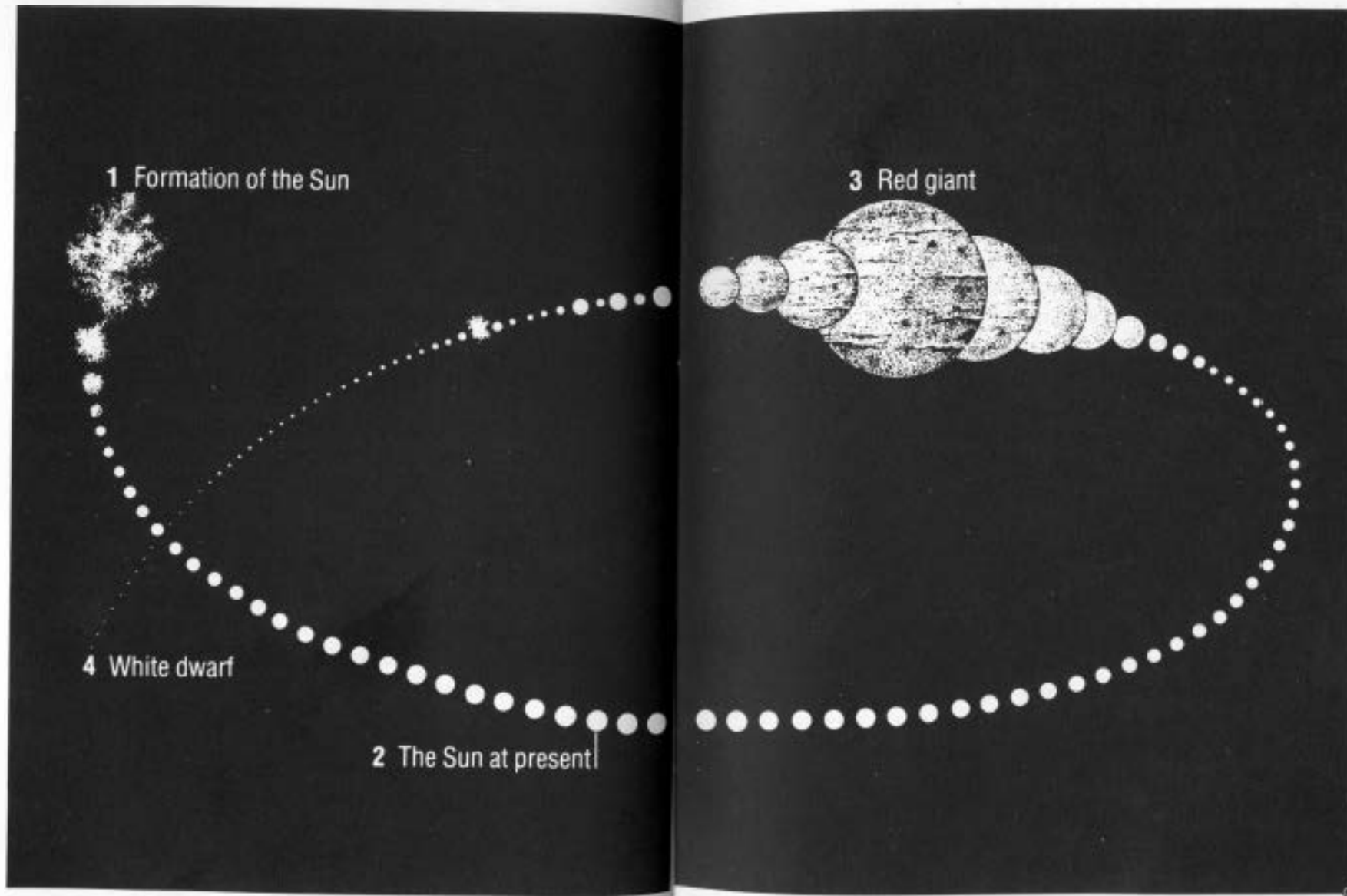
added heat causes the star to expand into a giant star. The surface of the star cools as this happens and turns red, which is why such a star is called a *red giant*.

When the hydrogen is nearly all gone, the nuclear fires move outwards to the thin, outermost layers of the star. These then expand into a gas and finally disappear. The inner layers, with almost all the mass of the star, now have no more energy to keep them hot. Gravity pulls these layers quickly inwards, and the star collapses. It collapses so quickly and gravity pulls so hard that just about all the electron shells collapse, and all the nuclei will come much closer together than they would in ordinary stars.

The star then has its mass squeezed into a small volume. It has become a white dwarf.

In the case of the Sun, this will not happen for about 5 thousand million years. It has already happened, though, to some stars that have run out of their hydrogen fuel. Sirius B and Procyon B are examples of this.

2. Limits and explosions

Gravitational pull is stronger as you get closer to the centre of any object, provided you stay outside the object.

Imagine yourself standing on the Sun. The gravitational pull on you would be 28 times what it is on the Earth. If all the mass of the Sun was packed more and more re tightly together and you still stayed on the surface, which would be contracting, you would get closer and closer to the centre and the gravitational pull on you would be stronger and stronger.

On the Sun's surface as it is, you are 695,200 kilometres from its centre. On the surface of Sirius B there would be the same mass under you, but you would be only 24,000 kilometres from the centre. If you were standing on the surface of Sirius B, the gravitational pull on you would be 840 times what it would be if you were on the surface of the Sun, and 23,500 times what it would be if you were back on Earth.

How do we check this? Can we tell whether Sirius B really has such an enormous surface gravity?

In 1915 a German-Swiss scientist, Albert Einstein, worked out a new theory of gravitation. According to this theory, when light moves outwards against a gravitational pull, all its wavelengths become a little longer. The stronger the gravitational pull, the longer the wavelengths.

The longest waves of light we can see are those of red light. This means that when light waves become longer, they seem to become redder—that is, they shift towards the red end of the spectrum. Einstein predicted a gravitational *red shift*.

Although the Sun's gravitational pull is much stronger than the Earth's, it is still not strong enough to do more than produce a very small red shift. That red shift is too small to measure accurately. But what about Sirius B, with its very strong gravitational pull?

In 1925 Adams, who had first studied the spectrum of Sirius B, did so again. He found that there *was* a red shift in the spectrum, just as Einstein's theory had predicted. Sirius B *did* have an enormous gravitational field.

That was the final proof that Sirius B was small and very dense. Of course, if that was what Sirius B was like, that was what all white dwarfs would be like. Our Sun will be like that someday in the far, far future.

But if gravitational pull becomes stronger and stronger as a star collapses, what stops the collapse and forms a white dwarf? Why doesn't the star collapse all the way?

Even after atoms have broken down and the electron shells are smashed, the electrons themselves still exist. They take up much more room than the nuclei do, and they keep the white dwarf from shrinking further.

The more massive a star is, however, the stronger its gravitational pull and the more tightly its matter is forced together. A white dwarf that is more massive than Sirius B would pull itself together more tightly and be smaller than Sirius B.

What happens if a white dwarf is very massive?

In 1931 an Indian-American astronomer, Subrahmanyam Chandrasekhar, studied this question. He was able to show that if a white dwarf was massive enough, it would force its way through the resistance of the electrons and collapse further.

He figured out just how massive a white dwarf would have to be in order to collapse further. It would have to be 1·4 times as massive as our Sun. That is called *Chandrasekhar's limit*.

The white dwarfs that astronomers have found and studied so far all have masses that are less than Chandrasekhar's limit.

This raises a problem.

If all stars are less than 1·4 times the mass of our Sun to begin with, then everything would be easily explained. The stars would all eventually become white dwarfs just as our Sun will. The trouble is that some stars have more mass than that. About 2·5 per cent of all the stars in the sky are more than 1·4 times as massive as the Sun. That doesn't sound like much, but there are so many stars altogether that even 2·5 per cent of them is a large number.

The stars in the Universe are collected into large groups called *galaxies*. Our own galaxy is made up of about 120 thousand million stars. That means there are about 3 thousand million stars alone in our own galaxy with masses that are over Chandrasekhar's limit. A few are even as much as 60 or 70 times as massive as our Sun.

What happens to them?

When astronomers studied massive stars, they found that the more massive a star, the shorter and stormier its life.

Different sizes of stars of the same mass

Red giant

Sun

White dwarf

Neutron star

Black hole
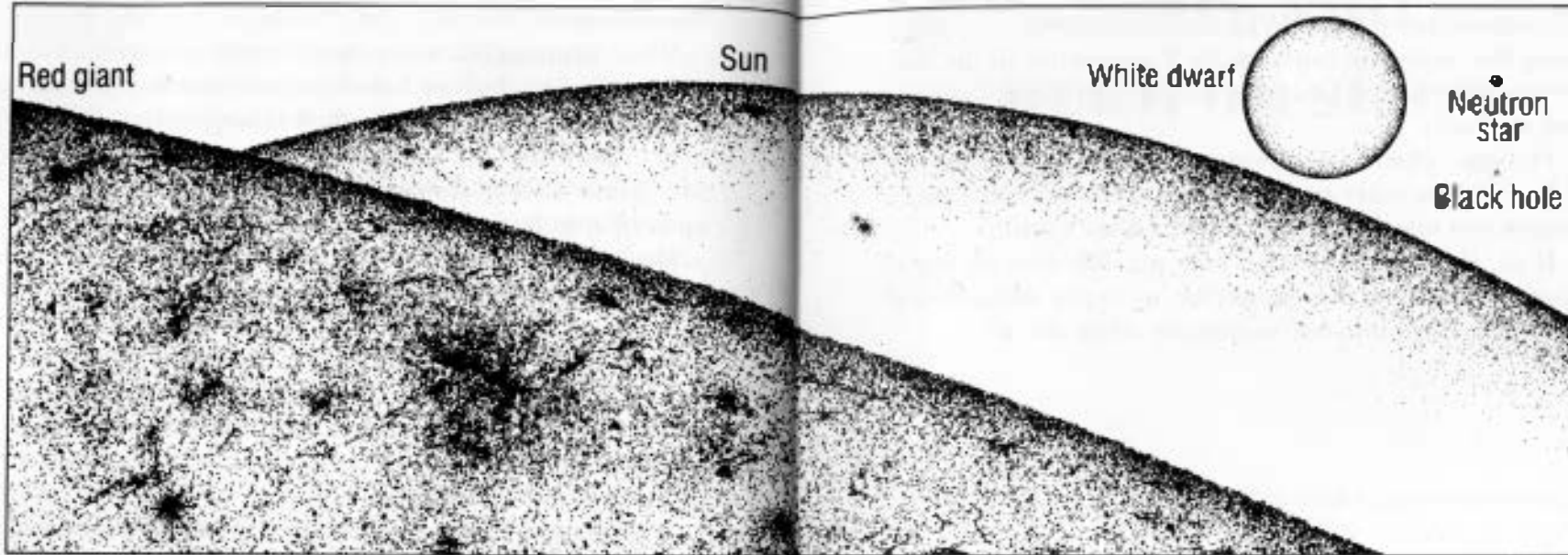
The more massive a star, the more tightly its gravity pulls it together and the hotter it must be to keep it from collapsing. The hotter it is, the more rapidly it uses up its hydrogen fuel. For that reason a massive star has a shorter lifetime than a less massive star.

It takes a star as massive as the Sun 10 thousand million years to use up its fuel, but a star three times as massive as the Sun will use up its fuel in only 300 million years. That is one reason that there are so few really massive stars. They do not last long.

Besides, the more massive a star is, the larger it expands when it becomes a red giant, and the more suddenly it collapses when the fuel is finally used up. When a star collapses suddenly enough, it explodes in the process. The

more massive it is, the greater the explosion. When a star explodes, it uses up all the hydrogen fuel still left in its outer layers. It does this very rapidly and the star glows up to 100 thousand million times as brightly as it did before, and it may keep on doing so for a few weeks.

Sometimes a dim star, one that is too dim to see without a telescope, becomes so bright it can be seen with the naked eye. To astronomers, before the invention of the telescope, it seemed that a new star had appeared in the sky. It was therefore called a *nova*, from a Latin word for "new".

Some novas don't become very bright and are the result of matter from another star falling upon them and glowing. Very bright novas result from actual explosions of massive stars and are now called *supernovas*

This seemed a possible way out of the difficulty of Chandrasekhar's limit. When a star turns into a supernova, the explosion hurls much of the matter in the star off into outer space. Only a small part of it hangs together and collapses.

Perhaps, when a massive star explodes, so much matter is hurled into outer space that the part that collapses is always less massive than Chandrasekhar's limit.

If so, that would mean it was possible that all stars, however massive they might be to begin with, would eventually turn into not-so-massive white dwarfs.

3. Pulsars and neutron stars

Not all astronomers were certain that supernovas were a way around the difficulties implied by Chandrasekhar's limit.

Some of them kept thinking about what might happen when a giant star exploded. It seemed to them that only a certain part of its mass could be thrown into space, and that might not be enough to bring it below Chandrasekhar's limit. In fact, it seemed to them a star couldn't possibly lose more than 90 per cent of its mass in a supernova explosion. If so, a star that was more than 15 times as massive as the Sun was sure to end up with a collapsing mass that was greater than Chandrasekhar's limit.

Besides, with massive stars, collapse could be so sudden that even if the mass of the collapsing part was less than Chandrasekhar's limit, the electrons might be smashed as the star squeezed together. What would happen then?

In 1934 the Swiss-American astronomer Fritz Zwicky and the German-American astronomer Walter Baade puzzled over this question. This is the way it seemed to them:

The nucleus in the atom is made up of two kinds of particles – *protons* and *neutrons*. They are very much alike, except that each proton has an electric charge whereas each neutron has none.

The electrons that exist outside the nucleus in ordinary atoms, and even in the smashed atoms of a white dwarf, also carry an electric charge. The electric charge on the electron is exactly the same size as that on the proton, but the two charges are of opposite kinds. The electric charge on the proton is called *positive*, and the one on the electron is *negative*.

If an electron and a proton are forced together and made to join, the two opposite electric charges cancel each other. What is left is a neutron, with no charge.

Zwicky and Baade felt that if the mass of a collapsing star was greater than Chandrasekhar's limit, or if the collapse itself was rapid enough, all the electrons would then be forced into the nucleus. The protons in the nucleus would become neutrons, and the collapsing star would then consist of nothing but neutrons.

With all the electrons gone, there would be nothing to keep the neutrons from coming closer and closer to each other until they touched. The collapsing mass would then become a *neutron star*.

Neutrons are so much smaller than atoms that a neutron star would be tiny. The Sun, for instance, is a big ball of hot gas 1,390,400 kilometres across. If all its electrons and protons were turned into neutrons, and it shrank till all its neutrons touched, it would become a neutron star not quite 6 kilometres across. But it would still have all the original mass of the Sun.

To Zwicky and Baade it seemed that white dwarfs would form only from stars that were too small to explode as supernovas. Stars large enough to go through a super-
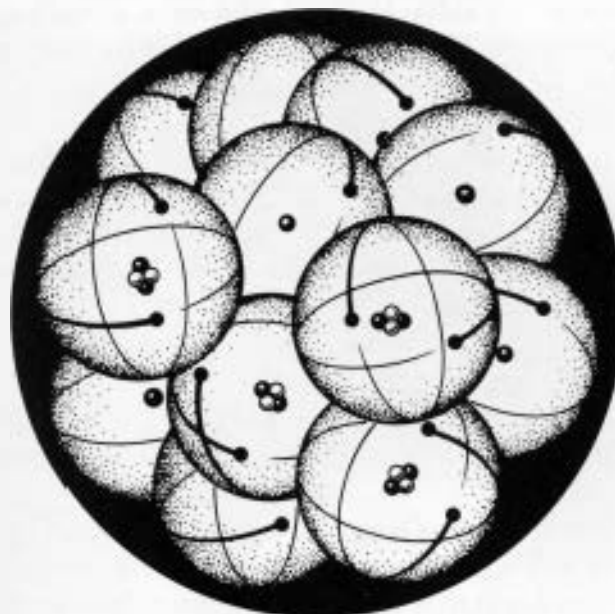
Collapse of atoms
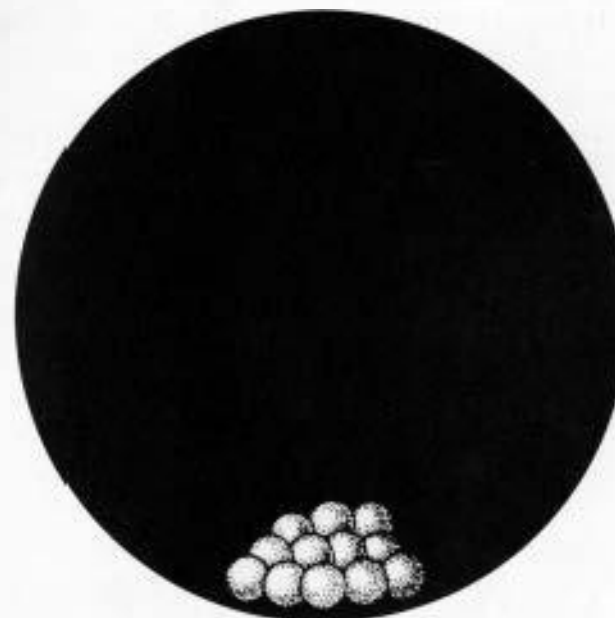
nova stage would collapse to neutron stars. (Our Sun is too small to explode. Some day it will collapse to a white dwarf, but not to a neutron star.)

But if a neutron star is only a few kilometres in diameter, how can we ever check the theory and find out if Zwicky and Baade are right? Surely even the best telescope wouldn't show us a tiny ball only a few kilometres in diameter when it is millions of millions of kilometres away from us.

Perhaps there is a way out. If a huge star collapses into a neutron star, the energy of collapse turns to heat. The surface of the neutron star should be at a temperature of 10 million degrees. That is almost as hot as the centre of our Sun.

A surface that has a temperature of 10 million degrees is too hot to give off much in the way of ordinary light. It gives off radiation that is like light but much more energetic. The more energetic such radiation is, the shorter its waves are, so the radiation given off by neutron stars consists of very short waves indeed. Such short-wave radiation is called *X rays*.

A neutron star should give off waves of all lengths, including those of ordinary light, and of radiation with still longer wavelength, such as radio waves. It should certainly give off X rays.

If we could study X rays coming from different places in the sky, then we could tell whether there are neutron stars somewhere out in space. One trouble, though, is that X rays can't get through the atmosphere. Ordinary light can, but X rays cannot.

Fortunately, beginning in the 1950s, scientists were able to send rockets into space beyond the atmosphere. Instruments carried by these rockets can study radiation from the sky before it reaches the atmosphere.

Crab Nebula
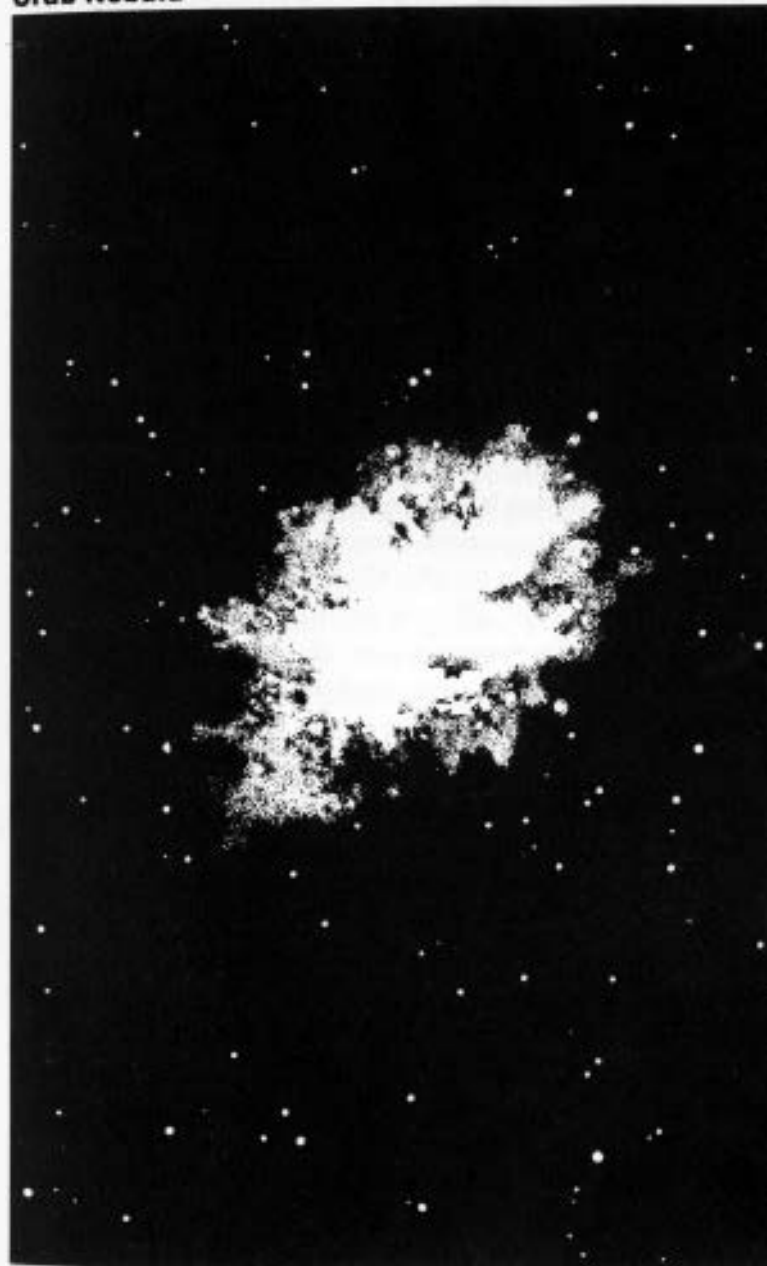
In 1963, under the direction of the American astronomer Herbert Friedman, rockets were sent out carrying instruments that could detect X rays. X rays were indeed found to come from different places in the sky, but were they coming from neutron stars or from other objects?

One of the places from which X rays were coming was the "Crab Nebula". The Crab Nebula is a patch of dust and gas; it is all that remains of a gigantic supernova that exploded in the year 1054. Could there be a neutron star in the middle of it?

That was hard to say. The X rays might be coming from the hot dust and gas—that is, there might be no neutron star at all.

In 1964 the Moon happened to pass in front of the Crab Nebula. If the X rays were coming from the dust and gas, it would take a while for the Moon to cover it all, and the X rays would be cut off little by little. If the X rays were coming from a tiny neutron star, the Moon would pass in front of it in almost no time, and the X rays would be cut off all at once.

The X rays were cut off little by little, and it seemed that there was no neutron star there.

However, that wasn't the end of the story. In 1931 an American engineer, Karl Jansky, had discovered that there were radio waves coming from the sky. Radio waves are like light waves except that they are much longer. Certain kinds of radio waves can get through the atmosphere as easily as light waves can, and these were what Jansky had detected.

In the 1950s astronomers built special instruments called *radio telescopes* to catch these radio waves and study them.

By the early 1960s it seemed to some astronomers that

in some cases the radio waves grew stronger and weaker very quickly. They seemed to be doing so more rapidly than the radio telescopes could catch the changes.

In 1967 a British astronomer, Anthony Hewish, had built a special radio telescope that would catch those very rapid changes.

It was set to work in July 1967, and within a month one of Hewish's students, Jocelyn Bell, was catching short bursts or *pulses* of radio waves from a particular place in the sky. Each pulse lasted only one-twentieth of a second, and came regularly every 1·33730109 seconds. They never vary in their timing by even as much as a hundred-millionth of a second.

Hewish and Bell looked elsewhere in the skies and soon found three more places where rapid pulses of radio waves could be found. Each one had a different period, of course. Naturally, they didn't know what produced these pulses, so they just called them *pulsating stars*. This was shortened to *pulsars*.

Other astronomers also located pulsars. In 10 years over 100 were found. There may be 100,000 of them in our galaxy altogether.

A pulsar located in the Crab Nebula has the shortest period yet found. The pulses come every 0·033099 seconds. That means one pulse every thirtieth of a second.

The Austrian-born astronomer Thomas Gold felt that in order to produce such pulses, some object in space must be going through some change very regularly and very rapidly. Two objects might be revolving about each other, or one object might be expanding and contracting or spinning on its axis.

There was a problem, though. To produce radio waves strong enough to be detected across distances of millions

of millions of kilometres, an object would have to be as massive as a star.

But ordinary stars couldn't move fast enough. Stars couldn't revolve about each other every second, or expand and contract every second, or rotate every second. Stars trying to move that quickly would tear apart. In order to undergo such rapid changes, an object would have to be much smaller than a star and would have to have a much stronger gravitational pull holding it together. Even white dwarfs wouldn't be small enough and wouldn't be held together by enough gravitational pull.

What about a neutron star? Gold decided that it had to be the answer. A neutron star is so small and has such a strong gravitational pull that it can turn on its axis in a second, or even in a thirtieth of a second without breaking apart.

Gold suggested that the radio waves might only come out of certain spots on the neutron star's surface. Each time the neutron star turned, a spray of radio waves would sweep out in our direction.

Gold also decided that as the neutron star sent out radiation, it would lose energy. Its rate of rotation should therefore slow down very gradually.

The pulsar in the Crab Nebula, for instance, has such a rapid period because the neutron star only formed about a thousand years ago and is the youngest we know of. It hasn't had time to slow down much, but it should still be slowing down.

The pulsar in the Crab Nebula was studied carefully, and Gold turned out to be right. Its period is getting very slightly longer each day. Each day the period is 36 thousand-millionths of a second longer than it was the day before.

Astronomers have pretty well decided now that pulsars

are indeed rotating neutron stars.

Of course, a rotating neutron star should be sending out all kinds of radiation, not just radio waves. The other kinds of radiation should also be reaching us in pulses. For instance, the Crab Nebula neutron star sends out pulses of X rays too. About an eighth of the Crab Nebula's X rays come from the neutron star. The remaining seven-eighths come from the surrounding dust and gas produced by the supernova. That seven-eighths is what made it look as though there was no neutron star there when the Moon passed in front of the Crab Nebula.

A rotating neutron star should also send out pulses of light. In January 1969, a very dim star inside the Crab Nebula was found to be going on and off 30 times a second. It was sending out pulses of light. It was the actual neutron star and astronomers could see it.

A second neutron star, in the debris of another supernova, has since been seen. This second neutron star is named "Vela X-1" because it is in the constellation Vela, the Sails.

In 1975, the mass of Vela X-1 was measured. It was found to have a mass 1·5 times that of the Sun.

The mass of Vela X-1 is over Chandrasekhar's limit. That is another piece of evidence in favour of its being a neutron star. An object with the mass of Vela X-1 couldn't possibly be a white dwarf.

4. Escape velocity and tides

A white dwarf may be very dense and may have a very strong gravitational pull, but a neutron star is far denser and has a far stronger pull.

Earlier in the book, I said that a cubic centimetre of material from Sirius B would have a mass of 34,600 grams. Suppose that, instead, we considered a cubic centimetre of matter from a neutron star with a mass equal to that of the Sun or of Sirius B. That cubic centimetre would have a mass of 1,550 million tonnes. A cubic kilometre of material from the neutron star would have a mass a thousand times as great as that of the whole Earth.

Suppose you weigh 50 kilogrammes. If you could somehow imagine yourself to be standing on the Sun, you would weigh 1,400 kilogrammes. On Sirius B you would weigh nearly 1,060 tonnes. On a neutron star with the mass of the Sun, however, you would weigh 14,000 million tonnes.

A strong gravitational pull doesn't have to mean that you can't ever get away. If you move quickly enough, you can move away from even a large object. The reason for this is that gravitational pull weakens with distance.

As an object moves away from Earth, for instance, the Earth's gravity pulls at it, slows it down, and eventually makes it return. If the object moves quickly enough, however, it can get so far from the Earth while it is slowing down that the Earth's weakening gravitational pull can't quite slow it down all the way. The object keeps moving away and never comes back.

The speed that is needed to get away altogether is called the *escape velocity*.

For the Earth the escape velocity is 11 kilometres a second. Any rocket that can reach the top of the atmosphere and is going at a speed of 11 kilometres per second will not fall back to Earth.

The Earth's escape velocity is large, but not too large. We can send rocket ships away from the Earth. Larger bodies would be harder to get away from.

For Jupiter, which is a larger planet than the Earth and which has a stronger gravitational field, the escape velocity is 60.5 kilometres per second. For the Sun, it is 617 kilometres per second, and for Sirius B, it is 3,400 kilometres per second.

If we consider a neutron star with the mass of the Sun, the escape velocity from its surface is 192,360 kilometres per second. It would be difficult indeed for anything on a neutron star to get away from its grip.

Light can, though. It travels at a speed of 299,346 kilometres per second. So do the other radiations that are made up of similar waves but that are longer or shorter in wavelength than light is. Radio waves can get away and so can X rays. That's why we can detect neutron stars.

If you double your distance from the centre of any astronomical body, its gravitational pull is cut to one
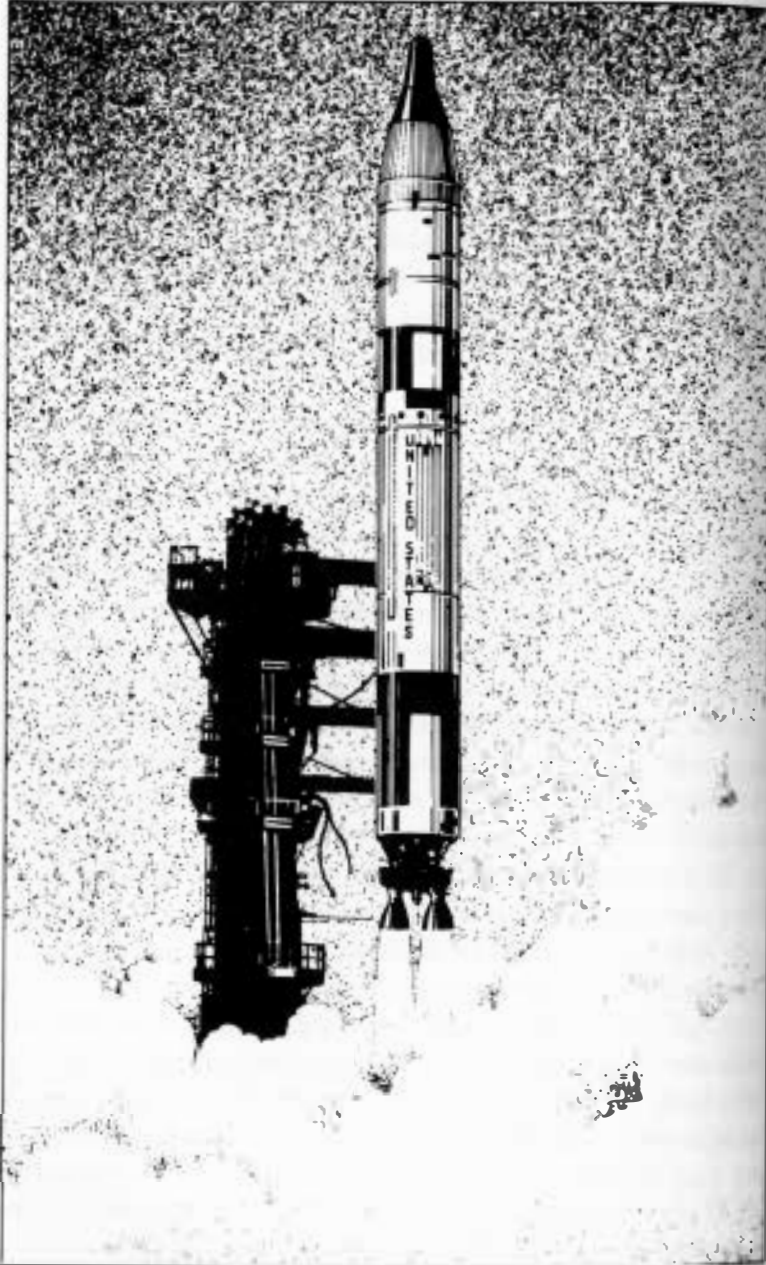
quarter. On the Sun's surface, for instance, you are 695,200 kilometres from its centre. If you moved 695,200 kilometres out into space, you would have doubled your distance from the Sun's centre, and the Sun's gravitational pull would be reduced to a quarter of its value on the surface.

On the surface of a neutron star, you would be only 8 kilometres from the centre. At a distance of only 8 kilometres above the surface, you would have doubled your distance from its centre and its gravitational pull would have been reduced to only a quarter what it was at the surface. The neutron star's gravitational pull drops very quickly with distance, therefore.

Imagine yourself very close to a neutron star with your feet pointing towards it. Your feet would be closer to it than your head would be, so that your feet would feel a stronger pull. The neutron star's gravitational strength drops so quickly with distance that even across the small distance from your head to your feet, the gravitational pull would change noticeably. With your head and feet pulled by different strengths, you would be stretched with considerable force.

This stretching is called a *tidal effect*. This can be felt even with weak gravitational pulls if the object feeling the pull is large enough. The Moon's gravitational pull stretches the Earth a little bit. Water heaps up a little on the side facing the Moon and on the side away from it. This produces the tides, and that is why the stretching is called a tidal effect.

5. Total collapse

How massive can a neutron star be? The more massive it is, the stronger the inward gravitational pull. If that gravitational pull gets strong enough, might it not smash the neutrons making up the neutron star? Or can the neutrons stand anything?

This question was considered, in 1939, by the American physicist J. Robert Oppenheimer. It seemed to him that the neutrons could *not* stand anything.

If a collapsing object was more than 3·2 times the mass of the Sun, then it would not only smash the electrons as it collapsed, it would also smash the neutrons.

What's more, after the neutrons were smashed, there would be nothing else—nothing else at all—that could stop the object from collapsing to zero.

If an object the mass of the Sun collapsed, its total gravitational pull would not change. If you were far away from the collapsing mass, you wouldn't notice any change as the collapse went on.

If you imagined yourself standing on the surface of the

mass as it collapsed, though, that would be different. You would be coming nearer and nearer to the centre as it collapsed, and you would therefore feel a stronger and stronger gravitational pull.

By the time the mass had collapsed to the white dwarf stage, you would weigh over 1,016 tonnes. When it reached the neutron-star stage, you would weigh 15,000 million tonnes. As the mass kept collapsing past the neutron-star stage and shrank to nothing, you would weigh more than 15,000 million tonnes—and more—and more—and more.

The tidal effect would become stronger—and stronger—and stronger.

The escape velocity would get higher—and higher—and higher.

The escape velocity is particularly important. As an object collapses *past* the neutron-star stage, the escape velocity rises till it becomes greater than 299,783 kilometres per second. When that happens, light, radio waves, X rays, and similar radiation can no longer leave the object. They don't move quickly enough. Neither can anything else, since scientists are quite sure that nothing can go faster than the speed of light. If light can't escape, neither can anything else.

The distance from the surface to the centre, when an object collapses to the point where light cannot escape, is called the *Schwarzschild radius*. It was first calculated by a German astronomer, Karl Schwarzschild.

For an object with the mass of the Sun, the Schwarzschild radius is about 2·9 kilometres. It would be 2·9 kilometres from the surface to the centre and then another 2·9 kilometres out to the opposite surface. That means that if the Sun shrank down to a sphere that was 5·8 kilometres across, keeping all its mass, light could no

**A black hole, with fragments falling in
and nothing coming out**

longer escape from it. Neither could anything else.

Imagine such a small object somewhere in space. Anything that passed close enough to it would be trapped. Tidal effects would pull it apart into tiny fragments. The fragments would circle the small object and eventually fall in. Anything that fell in could never get out.

With things falling in and nothing coming out, the tiny object would be like a hole in space. Because not even light or any other form of radiation would come out, it would seem absolutely black. It would therefore be a *black hole*, and that is what astronomers call it.

6. Finding black holes

Can we detect a black hole in any way?

If one was close enough to us, we could feel the gravitational effects, but suppose there was a black hole out there among the stars, very far from us. Could we tell it was there?

That doesn't seem likely. A black hole with the mass of the Sun would have less than half the diameter of a neutron star. What's more, a black hole would not be sending out pulses of radiation.

With so small a size and with nothing to catch in the way of radiation, how can we possibly detect a black hole?

It might be that we just can't. Black holes may just be something astronomers can talk about without ever knowing for sure whether they actually exist or not.

Fortunately, there is a possible way out. Although no radiation might come out of a black hole, matter that falls into a black hole would give off radiation *as it fell*. It would give off X rays.

Any small bit of matter that fell into a black hole would only give off a small quantity of X rays. There wouldn't be enough to detect at distances of millions of millions of kilometres.

Suppose, though, that there was a great deal of matter falling into a black hole all the time. Then the X rays might be given off in such large amounts that they could be detected.

It does not seem very likely that a great deal of matter would be falling into a black hole. The trouble is that space is so empty. Suppose our Sun turned into a black hole. The planets would still circle about it at great distances and would not fall in. Nor would there be much of anything else near the Sun to fall in.

But that is because the Sun is a single star; it is all alone except for its planets. Nearly half the stars in the sky exist in pairs, however. It is very common to have two stars circling each other, quite close together. Sometimes each star is more massive than the Sun.

Suppose we imagine such a pair of massive stars circling each other. The larger one would run out of fuel first, expand to a huge, red giant, then explode as a supernova.

The supernova would hurl much of its mass outwards, and what was left would collapse into a black hole. Some of the mass tossed outwards in the explosion would fall into the other star, which would become much more massive than it was before.

The black hole and its sister star would continue to circle each other. The sister star, more massive than it was before, would now use up its fuel more rapidly and begin to swell into a huge red giant itself.

The outermost layers of the new red giant, on the side facing the black hole, would be pulled towards the black hole by tidal effects. Matter would leak across from the

Red giant and smaller white star circling each other
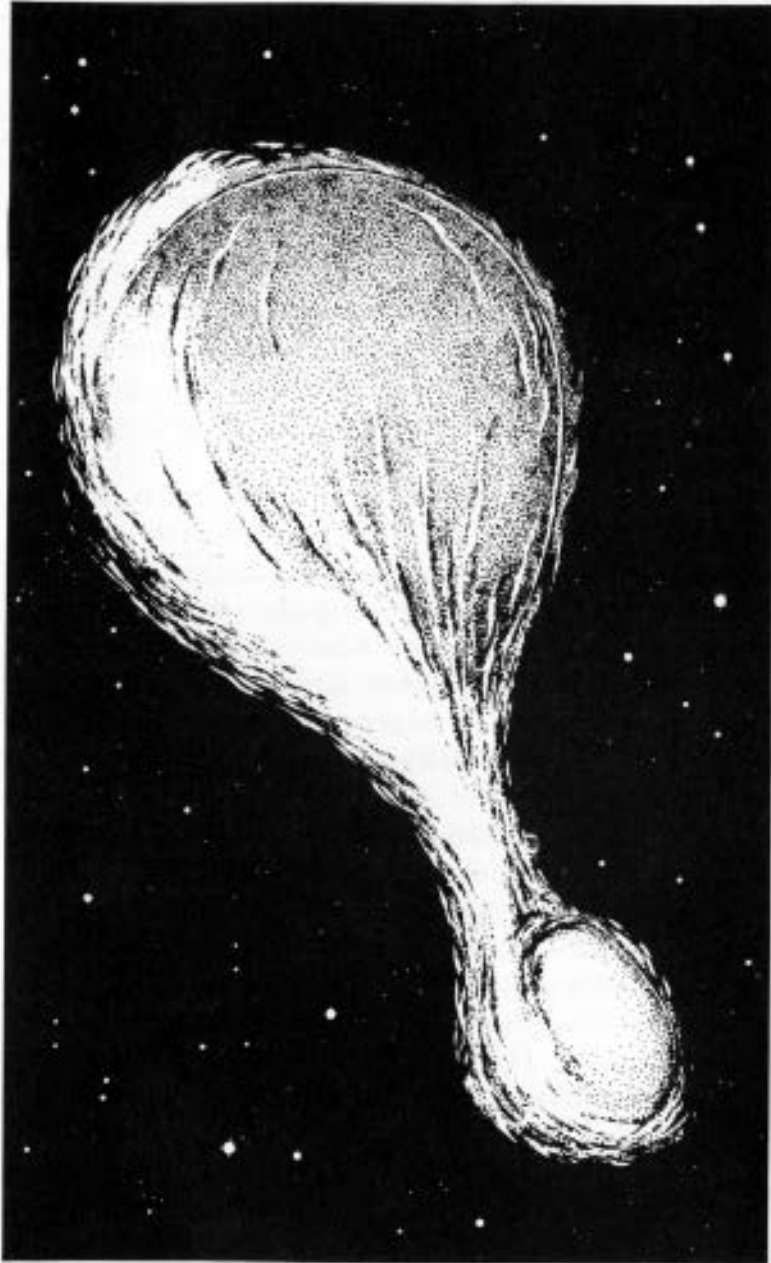
ted giant into the black hole, giving up large quantities of X rays as it did so.

This would go on for thousands of years, and during all that time X rays would be sent out into space in every direction, in quantities great enough to detect even at huge distances.

Astronomers on the Earth would have to consider the places in the sky where X rays were coming from. If the X rays came from a single point, it would mean they were coming from a collapsed star, either a neutron star or a black hole.

If it was a neutron star, the X rays would be coming out in rapid pulses as the neutron star rotated. If it was a black hole, the X rays would be coming out all the time, for they wouldn't be coming from the black hole but from the material falling into it. In the case of a black hole, the X rays might be coming out in greater and smaller quantities in an irregular way, since at times more matter might be tumbling in than at other times.

One of the first X ray sources detected in the sky was picked up in 1965 in the constellation Cygnus, the Swan. It was a particularly strong source and was called "Cygnus X-1". When pulsars were first discovered 2 years later, some astronomers wondered if Cygnus X-1 might not be a pulsar, too, and therefore a neutron star.

Astronomers were just learning about X ray sources, however, and they didn't have enough information to be able to tell.

Then, in 1969, a special satellite was sent into space with instruments for detecting X rays. The satellite detected and located 161 X ray sources, and for the first time astronomers had a great deal of material to work with.

By 1971 the instruments on that satellite showed that the X rays coming from Cygnus X-1 varied in intensity in

an irregular way. That meant Cygnus X-1 couldn't be a neutron star. Astronomers began to wonder if it might be a black hole.

They studied the place in the sky from which the X rays were coming and discovered that radio waves were coming from there too. Using both the X rays and the radio waves, the astronomers located the spot in the sky very accurately. It turned out to be very close to a visible star. That star was listed in the catalogues as HD-226868.

HD-226868 is a very dim star because it is very far away. It may be as much as 10,000 light-years away, which would make it about 1,100 times as far as the star Sirius.

Once you allow for that distance, it turns out that the star is a large one with about 30 times the mass of the Sun. Also, this large star is not a single star at all, but is moving around another star once every 5.6 days. To be making the circle that quickly, the two stars must be quite close together.

The X rays are not coming from HD-226868 but from a spot very close to it. In fact, the X rays are coming from the companion of HD-226868, from the star that HD-226868 is circling.

From the rate at which HD-226868 is making its turn, it is possible for astronomers to calculate that the companion star has 5 to 8 times the mass of the Sun.

Yet when one looks in the place where the companion star must be, there is *nothing there to see*. If it was an ordinary star that was 5 to 8 times the mass of the Sun, then it would be bright enough to see in the telescopes even if it was 10,000 light years away.

Because it cannot be seen, it must be a collapsed star. A white dwarf or a neutron star might not be seen at that distance, but neither a white dwarf nor a neutron star

could be that massive without collapsing further.

For all these reasons, many astronomers think that Cygnus X-1 is indeed a black hole, the first to be discovered. There may be many more.

As we have seen, black holes can be formed when stars collapse. Such black holes end up with a mass equal to that of stars and grow constantly as they pick up more and more matter. On the other hand, even small bodies can become black holes if they are pressed together hard enough.

In 1971 an English scientist, Stephen Hawking, suggested that this happened when the Universe first began in a "big bang". As all the matter that now makes up the Universe exploded, some of the matter may have been squeezed together so tightly in the process that small black holes were formed. Some of those black holes might only have the mass of small planets or even less, and they are called *mini-black holes*.

Hawking also showed that black holes *can* lose mass after all. Some of their gravitational energy is changed into particles outside the Schwarzschild radius and these particles might escape. Such escaping particles carry off some of the mass of a black hole, which "evaporates" in this way.

For large black holes with the mass of a star, the rate at which they evaporate is so slow that it would take many millions of millions of years for the black hole to be gone. In that time it would gain much more mass than it loses, so actually it would never evaporate.

The smaller the black hole, the faster it would evaporate and the less chance it would have to gain mass.

A really small black hole would lose mass faster than it could gain mass. It would get smaller, therefore, and then it would evaporate even faster and get still smaller. Fin-

Red giant in orbit with black hole

ally, when it was very, very small, it would evaporate all at once in a kind of explosion that would send out radiation that was even more energetic than X rays. The radiation sent out would be *gamma rays.*

Mini-black holes that were formed at the time of the "big bang", 15,000 million years ago, might just be disappearing right now. Hawking calculated how big they would have had to be to start with and what kind of gamma rays they would produce as they exploded.

If astronomers could detect just the kind of gamma rays Hawking predicts there should be, that would be good evidence that mini-black holes were formed and that they exist. So far, though, the proper gamma rays have not been detected.

But they might be at any time. And there's still Cygnus X-1.

Astronomers may soon learn much more about black holes and perhaps discover some amazing things about them that will help us all to understand the Universe better than we have in the past.