SPACETIME SINGULARITIES: The STORY of BLACK HOLES

We have already seen that the Big Bang is a kind of 'singularity' in the structure of spacetime. To the question "what was before the Big Bang?", one can reply, at least in the context of GR, that the question actually has no meaning - that time has no meaning 'before' the Big Bang. The point is that the universe can be finite in extent in both time and space, and yet have no boundary in either. We saw what a curved space which is finite in size but has no boundary means for a 2-d surface - a balloon is an example. Notice that if we made a balloon that curved smoothly except at one point (we could, for example, pinch it at this point) we could say that the balloon surface curvature was singular (ie., infinite) at this point. The idea of a 4-d *spacetime* with no boundary in spacetime, but with a finite spacetime 4-dimensional volume, is a simple generalization of this. And just as it makes no sense, inside a 2-d balloon, to ask where the boundary is, we can have spacetime geometries which have no boundary in space or time, or where spacetime 'terminates' at a singularity.

All of this is easy to say, but the attitude of most early workers in GR was to ignore the possible existence of singularities, and/or hope that they would just go away. The reaction of Einstein to the discovery of singular solutions to his equations was quite striking. In the period 1938-39, Oppenheimer and his students Snyder and Volkoff investigated what would happen in GR to a massive star that collapsed, and discovered what we now would call a 'black hole' solution to the mathematical equations. But Einstein rejected this as an abomination, and adopted the attitude that Nature would never allow such a thing. It has to be assumed that Einstein felt that GR itself, as a theory, would either (i) break down in the region of a singularity, and that some more advanced theory would rule out such singularities; or (ii) that some as yet undetermined principle in GR would forbid such singularities. The authority of Einstein meant that few people spent any time investigating singular solutions to GR for some 20 years thereafter.

However the situation changed dramatically in the 1960's. Some remarkable mathematical work by R Penrose, later extended by Penrose and Hawking, established that not only were the singular solutions legitimate solutions of the GR equations, but that much more important, they were almost *inevitable*. To put this another way - no matter what kind of universe one had, there had to be singularities in it somewhere! This purely theoretical work coincided roughly with several other developments, all in the 1960's, as follows:

(i) The discovery of the microwave background, which meant that the Big Bang was here to stay - see the previous document;

(ii) the discovery in 1962 of quasars, or QSO's (short for "quasi-stellar objects"); these looked like stars, but had colossal redshifts, apparently placing them billions of light years away;

(iii) the discovery in 1967 of pulsars (named thus because of their very rapid pulsing, sometimes with period of hardly more than a miilisecond); within 6 weeks T Gold realized that these were the incredibly dense "neutron stars", first discussed by Landau, Zwicky, and Oppenheimer and Volkoff in the 1930's.

Added to this was the gradual realization that much of the universe was an incredibly violent place, with processes going on involving unimaginably high energies and very strong gravitational fields. This gave a very strong boost to the study of what came to be known as 'relativistic astrophysics', a subject pioneered to a considerable extent by the Soviet astrophysicist YB Zeldovich and his collaborators.

We now know that supermassive black holes are at the centres of almost all galaxies, and that scattered throughout these galaxies are much smaller black holes left over from massive supernova explosions. Far from being a mathematical pathology, as Einstein thought, they are a crucial part of our universe. In what follows we explore some of this.

A: STRUCTURE of BLACK HOLES

The mathematical theory of black holes and spacetime singularities is considered to be one of the most difficult (if not *the* most difficult!) parts of physics to understand. Thus in what follows I will only offer a very 'watered-down' version of what we know. We will begin with what is called the 'Schwarzschild black hole'. Rather than discussing this as a solution of Einstein's field equations, we begin by examining its physical origin, as the end-product of the collapse of a massive star. The Schwarzschild black hole forms a point singularity in spacetime - although, as we will see, one can in theory open this up to give a wormhole (albeit this seems unlikely in practise). However it suffers the severe limitation of describing a black hole which is not spinning. A spinning black hole is described by the 'Kerr solution', which is much more interesting. We discuss this, and thereby prepare the way to understand how real black holes work.

Before we discuss exactly what a Black Hole looks like, it is useful to know how and why they form in the first place (in fact, since black holes are objects in spacetime, we can't actually separate their behaviour in time from their behaviour in space).

Let's start with *why* black holes can form. As we have already seen, General Relativity is what mathematicians call a *non-linear* theory. If we increase the spacetime curvature in some region, then this curvature has energy (rather in the same way that energy is stored in a stretched membrane or string). But as we have seen, the presence of mass-energy in some region of spacetime will itself cause curvature. Thus we have the peculiar situation that "gravity acts as its own source", ie, that a region of strong curvature, because it carries energy, will tend to try and produce even more curvature. Clearly there is a danger here of the whole process going out of control, ie., that the curvature will continue to increase as it 'generates itself' until it becomes infinite - this is the non-linearity of the theory. The final result of this can have various 'shapes', which we will look at below, but all of them have one thing in common, viz., that the spacetime does become singular (ie., the curvature becomes infinite) at either a single point or on a line. And of course since the gravitational force experienced by any object in the vicinity of this region is just proportional to this curvature, the attraction caused by this singularity becomes irresistible - nothing can escape if it is too close.

In essence, this tendency for the spacetime curvature to feed on itself and become infinite is why a black hole can form. Obviously this process will not work if we only start off with a small initial curvature (caused, eg., by some small mass like the earth). This small curvature will generate some even smaller extra curvature, but this is where it stops. However, we can imagine starting off with a very large and compact mass, and if it is big enough, the 'runaway' process we just described becomes perfectly feasible. Of course things are not quite so simple, because the initial matter that has set off the process will try and resist being compacted by the strong attraction. But in fact one can show that in the end, nothing can resist the singularity once it has become strong enough. This is because any matter, in order to resist the attraction, will have to acquire a huge amount of kinetic energy (coming from a high velocity, near that of light, which it needs to try and escape). But if it has a high kinetic energy, this energy will itself generate more curvature! Thus the more energy we give an object, in an effort to help it escape, the stronger will be the curvature this generates around the body, and thus the stronger the force pulling it back (this we might call the 'Thor mechanism', after the legend of the Norse God Thor, who when he tried to lift a snake that girdled the Earth, found that the more force he exerted, the stronger was the force that resisted).

A.1: The SCHWARZSCHILD BLACK HOLE

Let us now turn to the much more complicated question of *how* black holes form in the universe. As we shall see below, in section A.2, there are really two kinds of black hole that we know of. The first is formed in the wake of a supernova explosion, and has a mass ranging between perhaps 3-10 solar masses. The second, the so-called 'supermassive black hole', is formed at the centre of galaxies, and these can have enormous masses, ranging up to as high as 20 billion solar masses. Monsters like these control the entire galaxy in which they are found, and have an influence way outside their home galaxies. The way in which they form is still being unraveled. In any case, the formation of any kind of black hole is almost always a very violent event, of great complexity.

A.1(a) Stellar Collapse to a Black Hole: Despite the complexity of a real back hole, we would like to first understand the basic ideas, and this means a simplified model is required. Without going into the details, let's assume here a very simple 'toy model' for the formation of a black hole, in which a large mass contracts to a very high density, small diameter object - we can think of it s a kind of 'spherical dust' model. This toy model is shown in Fig. 1(a). We will this ignore all of the real physics, in which this contraction happens very rapidly and liberates huge amounts of energy in an explosion; and we also assume the black hole is not rotating, and that everything is spherically symmetric. The use of such toy models is justified if they allow us to isolate out some of the real physics. The kind of model we are talking about here is not so different from the one used by Oppenheimer and his students in 1938.

Consider first the situation when the star is still large. Then the gravitational field near its surface is still fairly weak, and if we imagine a source of light near the surface, emitting light in all directions, we see that the way in which this light propagates out will be hardly affected by the gravitational field of the star (so that, as shown in Fig. 1(a), left image, the light beams head out radially from the light source). In Fig. 1(a), right-hand image, we see how this looks like on a 'spacetime diagram', in which time is shown increasing upwards, and the distance away from the centre of the star is shown horizontally. The light beams from the light source move away in straight diagonal lines in this situation, at early times when the star is still large. This is because they are moving at a constant velocity c_o, the velocity of light, so their distance away increases in proportion to the time elapsed.

Now consider what happens as the star contracts. Near its surface, the gravitational field becomes ever stronger, so that the light paths begin to bend back towards it, and light has more and more difficulty escaping the star. This is seen in the series of 'snapshots', taken at different times, of the star (cf. Fig. 1(a), left image), and in the spacetime diagram at right, where the light paths begin to bend in (ie., curve upwards) as time goes on. Finally, an event

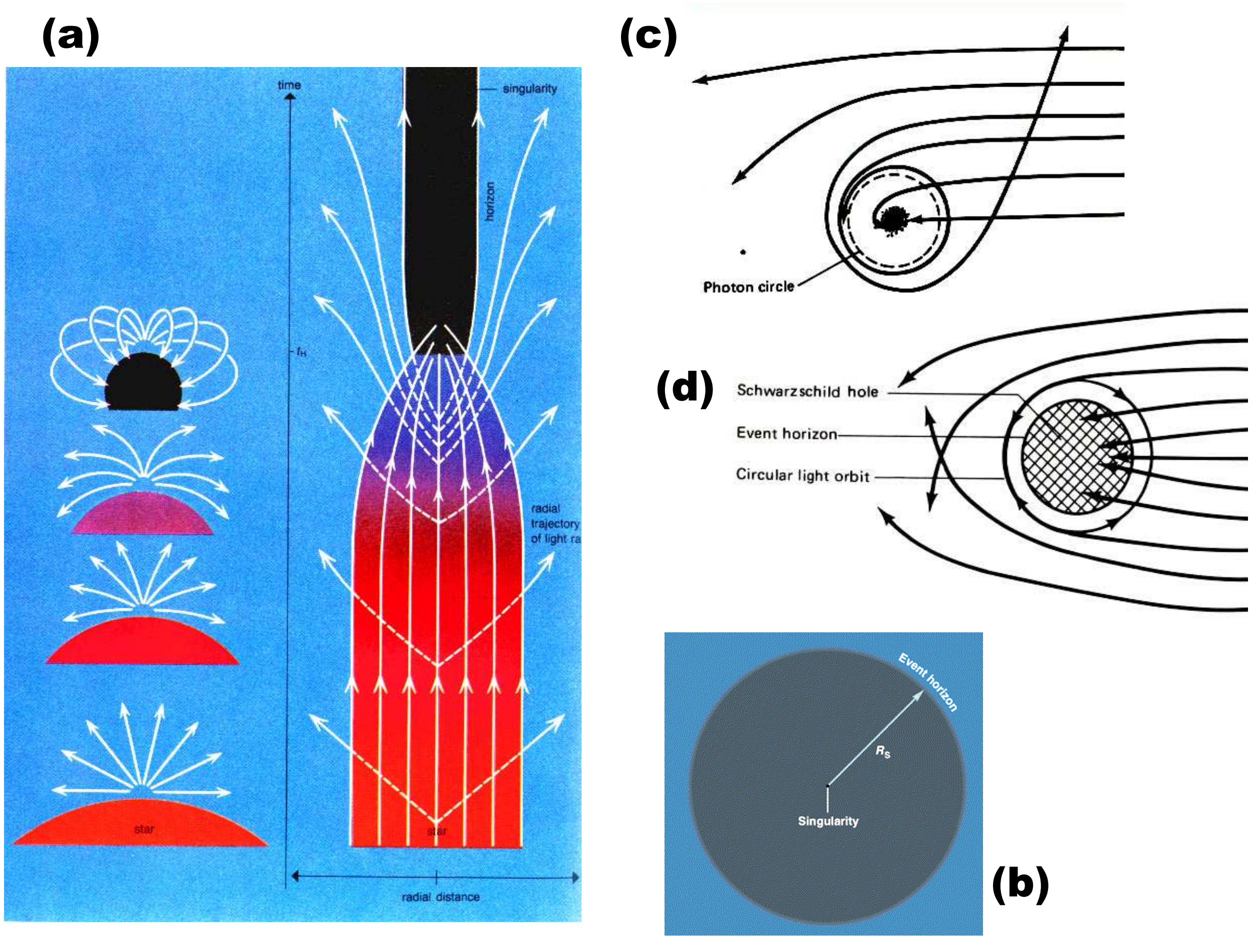

FIG. 1: Simple non-rotating Black Holes. In (a) we see how the hole can form. In the left-hand image, we see 'snapshots' of a star collapsing, and the paths of light rays emitted from near its surface are shown in white; everything below the event horizon is shown in black. In the right-hand 'spacetime diagram', elapsed time is plotted vertically, distance away from the centre is plotted horizontally. We plot the paths of matter (vertical white lines) and of light rays (hatched white lines radiating out sideways). In (b) we show the spacetime structure around a Schwarzschild black hole. In (c) we show the paths of light rays passing near to a black hole, and in (d) we see the same thing, but now for a set of parallel light beams passing on either side of the black hole.

horizon begins to form. This event horizon is defined as the surface below which the gravitational field is so intense that any light emitted outwards simply cannot escape. Inside the event horizon, a spacetime singularity forms at the centre - everything inside the event horizon must then fall towards the central singularity, including light. On the event horizon surface itself, any light emitted outwards will simply sit at the event horizon. This is seen in Fig. 1(a), right image, where light beams emitted from the event horizon point up vertically, meaning that as time goes on, they do not chage thier position. In this figure, we have shown a situation where all the matter continues to fall inwards, and eventually gets eaten by this black hole. Thus, once formed, the black hole continues to grow in size until it has eaten everything. Moreover, we have shown a spherically symmetric black hole, for which the event horizon is spherical, and everything falls directly towards the centre. This spherically symmetric black hole is called a "Schwarzschild black hole", since Schwarzschild's 1916 solution of Einstein's equations actually describes this system. It is the simplest kind of black hole.

Having seen the how and the why of black holes, now let's look at their structure - what do they look like? The first question we can of course ask is - how big is the black hole? Actually, the result turns out to be very simple. The radius of the black hole event horizon - called the "Schwarzschild radius" - turns out to be simply proportional to the mass inside the event horizon. The structure of spacetime around this Schwarzschild black hole is shown in Fig. 1(b); the event horizon is spherical, with a Schwarzschild radius R_s. The result one finds for R_s is not large. In fact, if the mass of the black hole were equal to that of the sun, the Schwarzschild radius would be only 3 km, and a black hole with the mass of the earth would have $R_s \sim 9mm$! What this means is that we would have to cram the entire mass of the earth into a region of diameter less than 18mm (just over the size of a dime) before the gravitational field exerted by this mass would be strong enough to hold back light, and for it to collapse into a black hole. Any objects in your ordinary everyday experience would have minuscule Schwarzschild radii - for example, the Schwarzschild radius of Grouse mountain would be hardly larger than a large atomic nucleus - it would be roughly 10,000 times less than the radius of an atom.

How would we 'see' a black hole? It is interesting to see what happens to any light coming in from outside towards the black hole. Obviously any light aimed directly at the hole will simply go straight into it, and never come back out. Light aimed slightly away from it, outside the event horizon, will be very strongly deflected from its initial path - gravitational light bending is no longer a weak effect. This situation is shown in Fig. 1(c), where we see that as the beam gets over closer to grazing the event horizon, it is pulled into a spiral path around the hole, from which it only just escapes. Thus the image of a black hole would simply be that of distorted light coming from *other* objects - the black hole itself would emit no light at all. We can also imagine aiming a set of parallel beams of light past a black hole (see Fig. 1(d)). In this case we see that the gravitational 'light-bending' effects are far stronger than we saw for the sun - in fact, beams passing close to the event horizon will be very strongly deflected, and if the graze the event horizon they will enter into a circular orbit around the black hole. This of course is the picture given by treating the light according to classical optics, ie., as simply thin beams. In reality we know that light is a wave, and so our picture of parallel beams should be replaced by a wave-front coming in from the right. You can see that the wavefront will be strongly distorted, and indeed the black hole will behave a little like a "circular slit" (ie., instead of a 'double slit' in a screen, a circular annular opening in the screen). Thus waves will be focussed behind the screen in a rather interesting pattern.

At first glance the spherically symmetric Schwarzschild solution to Einstein's equations seems awfully artificial. After all, common sense tells us (and both calculations and the observation of supernovae confirm) that the collapse is going to be a very messy process, even if the system is almost exactly spherically symmetric at the beginning, before the collapse starts. In fact all sorts of instabilities can and do develop in the process of the infall of material, even before an explosive rebound takes place, and the explosion is not all that symmetric. In section C.2(a) below we will take a more extended look at what supernovae and their remnants look like, to see this.

However, it can be shown that if the initial collapsing material does not have a net angular momentum (ie., it is not spinning), then even though the infall and the explosion may look very disorganized and not in the least symmetric, nevertheless the final black hole *will* be symmetric. What happens is that even if the initial black hole event horizon is not spherically symmetric, it will very quickly adjust itself (by radiating away gravity waves, etc.) to a quiescent spherically symmetric state - and stay that way thereafter. For this reason one can learn a great deal about black holes from the Schwarzschild solution - it is not such a bad toy model after all.

A.1(b) The 'Wormhole' solution: Interestingly, the Schwarzschild solution can be extended even further, as was realized by Einstein and Rosen as early as 1938. What they understood, and what has become much clearer in recent years, was that the structure of spacetime around a non-rotating Schwarzschild black hole is somewhat more complicated than the simple picture in Fig. 1(b). This is because one can envisage another region of the universe 'joining up' with the black hole, in a way which is shown schematically in Fig. 2(a). Suppose we go back again to the 2-d spacetime analogy, and imagine that we have a very large elastic sheet which we allow to 'go singular' at one point. This is the 2-d analogy of a black hole. But now there is nothing wrong with us 'bending' the large slowly around so that another quite different part of it comes close to the original singularity, and then a new singularity forms at this other part of the sheet. Fig. 2(a) attempts to show this process - the 2 separate sections of the sheet each have singularities, and these then join. What was later realized (and which has been explored in more detail in recent years) is that if there is a region of '*negative mass-energy*' density in the region of this 'bridge' between the 2 different regions of spacetime, it could actually open up for a brief time, to form what is now called a 'wormhole', connecting the 2 regions of spacetime. The form of this wormhole is shown in the vicinity of the wormhole in Fig. 2(a), and from a more global perspective in Fig. 2(b), where we see displayed the possibility of 2 very distant regions of the universe being connected in this way. Note that of course we are showing here simple 2-dimensional analogies to what is actually a 4-dimensional structure.

Now it is actually important to realize how strange is this idea of a negative mass-energy density - indeed, in classical General Relativity such an idea is meaningless. The possibility of this 'joining' of the two spacetimes was understood to be a mathematically interesting but physically meaningless result. Indeed, without the negative mass-energy density, all that one really had was a black hole singularity which could simultaneously be embedded in two larger spacetimes - there was no particular requirement that these two spacetimes even be part of the same universe. In the rubber sheet analogy, this means that there was no requirement that the 2 separate sections of sheet even be part of a single sheet - one simply had a single singular point at which they touched, and no wormhole was ever formed.

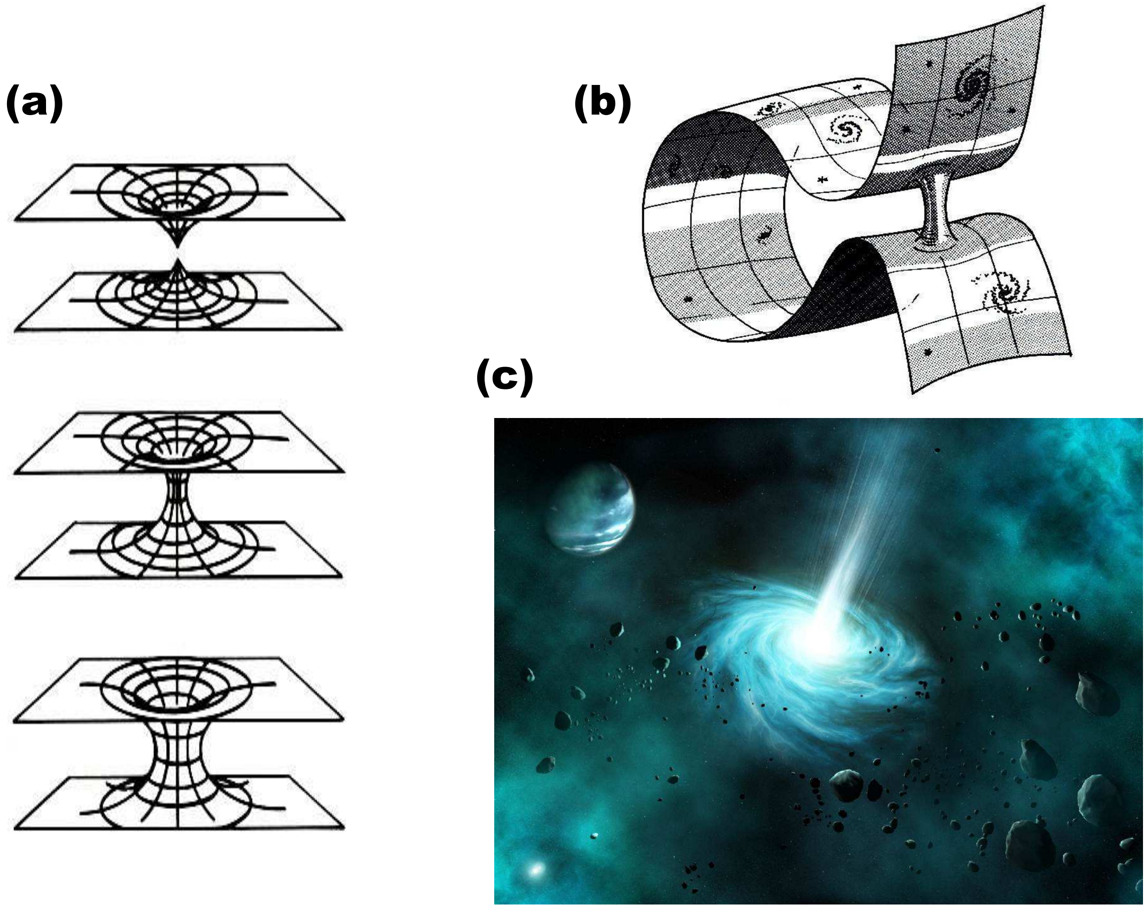

FIG. 2: Wormholes in spacetime. In (a) we see one scenario for the formation of a wormhole, as 2 projections from different regions of spacetime merge. In (b) the resulting structure of spacetime is shown. In (c) we see an artist's impression of what things would like near a small wormhole.

However, ideas on this topic have evolved in recent years. This is because of the realization, in the work of people attempting to understand how to combine quantum mechanics and relativity, that the background vacuum needs to be understood quantum-mechanically. In these circumstances, as was realized in particular by Hawking, it is possible for the vacuum energy density to develop a negative energy density in the region of the singularity. It is this result that is in fact connected to the idea of 'Hawking radiation', ie., the idea that a black hole can radiate and thereby lose mass. What actually happens is that the vacuum is destabilized in the vicinity of the singularity, and this allows radiation to 'quantum tunnel' into existence. To give a proper discussion of this requires some understanding of quantum mechanics, and so we delay it for later.

In any case, the mere possibility of negative energy then makes it possible to envisage the opening of a wormhole. Under these circumstances very strange possibilities can be entertained. One is the idea of time loops - by going through a wormhole and then coming back again, one can actually find oneself at an earlier time in the original region of space that one started from. In fact this is not the only possibility that exists of such time loops - there are other possible solutions to Einstein's equations that can also give these (such as the "Gödel universe", found by K Gödel in 1949 - this solution has the entire universe in uniform rotation). However it does now seem clear that no material object could pass through such a wormhole - it would be completely annihilated, even if the wormhole stayed open long enough for it to pass through.

For this reason the kinds of adventure that are occasionally envisaged in science fiction, in which wormholes are traversed by spaceships, are not supported by what we currently know. An image of such a scenario is shown in Fig. 2(c) (note that this image is not a good portrayal of a non-rotating wormhole of the kind that is typically discussed, since such a wormhole would appear in or 3-d space as a spherical entity - the picture could only be portraying a wormhole with some kind of rotation superposed on it). On the other hand one can seriously discuss the possibility of such object appearing a reappearing in our part of the universe, even if they could not be traversed. In fact, there are some scenarios (no more than scenarios at the present time!) which discuss the appearance of such 'fluctuations' at the very small scale. This is the idea of 'quantum foam', ie., that at the very smallest scale, spacetime is fluctuating wildly, with wormholes and all sorts of other strange configurations appearing a disappearing all the time. This is where science and science and science fiction touch other very closely.

Let us now descend (or perhaps re-ascend) from such speculations, and ask what we have understood so far here. We have in fact learnt a great deal about the physics of black holes already from the simple Schwarzschild solution and its relatives. What these all have in common is (i) that no rotation or angular momentum is involved, and (ii) the existence of a spacetime singularity and a surrounding event horizon. We have also seen that these black holes and wormholes can be formed by gravitational collapse. However, it is obvious that any real collapsing massive body will be rotating, and therefore have angular momentum; and so the Schwarzschild solution is from this point of view misleadingly simple. So let us now turn to a much more realistic solution.

A.2: ROTATING BLACK HOLES: the KERR SOLUTION

One of the reasons why physicists spent so long looking at symmetric (ie., Schwarzschild) black holes is that it is extremely difficult to solve the GR equations in more complicated situations. However in 1964, a relatively unknown New Zealander named R Kerr gave the solution for a rotating black hole. This result was a mathematical *tour de force*, and the results turned out not only to be extremely interesting, and very elegant, but of great practical importance. They are a little difficult to explain in detail; here I will give a somewhat pictorial overview.

Obviously it would be asking for too much to expect a star, or any other body, which collapses into a black hole to have no rotation at all. Indeed, since we know that the collapse will make the object spin ever faster as it gets smaller, we would expect that an already rotating star would end up as a very rapidly-spinning black hole. And all stars rotate to some extent - they are formed when clouds of gas and dust collapse under their own self-gravitation (a process usually initiated by some large disturbance in the interstellar medium, such as a shock wave from a supernova or some other source). Indeed, for many years a big mystery was how stars could form at all, since the gas clouds in question are usually very large (several light years across at least) and so almost any initial rotation of the cloud would turn into an extremely rapid spin once it had condensed down to the size of a typical planetary system - so rapid that it would actually fly apart, ie., it would never be able contract to a small enough size. We now know that this problem is solved by the magnetic fields inside the cloud - charged particles in the cloud can move out along the field lines, dragging gas with them, and this very efficiently allows the cloud to get rid of a lot of its rotation.

Be this as it may, we know that the end result of stellar nucleation and birth is a galaxy full of spinning stars (the sun spins relatively slowly - turning around once in 26 days - but most stars spin faster than this). So we expect any black holes formed from stars to be spinning very fast. Does this rapid rotation make a big difference?

The answer, shown in Fig. 3, is that it does, and in a very intriguing way. Let's start with Fig. 3(c) which shows a snapshot from the side of a Kerr black hole (ie., a rotating black hole), ie., what it looks like from the orbital plane, perpendicular to the axis of rotation. We now see that there is no longer a simple event horizon - in fact there are *two* horizons, and the region between them is called the 'ergosphere'. The outer horizon is sometimes called the rotational horizon; it marks the surface below which it is impossible to stop an object rotating, no matter how much force one might exert to stop it from rotating. However an object falling below this outer horizon into the ergosphere can still escape - in particular, light can escape from the ergosphere, provided it does not fall as far as the inner horizon. The inner horizon is just like the event horizon for the ordinary non-rotating Schwarzschild black hole - anything within cannot escape.

Perhaps the easiest intuitive way to think about the Kerr black hole is that it imparts a kind of 'twist' to spacetime. Any object moving through the region around it will feel this, and its motion will be affected accordingly. An example of this is shown in Fig. 3(d), which shows the path of a light beam coming into the black hole from above, (ie., along the axis) in such a way that it passes outside the ergosphere. We see that its motion acquires a 'spiralling' or twist component, while it is near the black hole (moreover, any solid object in this geometry would in fact be twisted and spun around, as well as being pulled/stretched around the black hole). Thus we see that a rotating black hole not only 'sucks' spacetime in towards it, but also twists it around itself. You can think, in the 2-d balloon analogy, of the elastic balloon surface not only being pulled in towards a point in the surface, but also twisted around it.

Another way of looking at all this is shown in Fig. 3(a), which repays careful study. Imagine that in Fig. 3(c) we take a 'slice' in space through the equator of the black hole - this slice defines the equatorial plane of the black hole. Then Fig. 3(a) shows us what we would see if we were in this slice. The gravitational energy of an object inside the slice is indicated by the funnel-shaped surface (so that the object is being 'sucked down' into the 'funnel'). At various points inside the slice we imagine putting down 'test lights', which emit light in all directions - these are the little red dots in the figure. A short time after the lights are switched on, we ask what has happened to this light, ie., how far it has propagated. At points far out from the black hole, we see that the light has propagated out in all directions at the same speed, so we get a circle-shaped light region expanding away from these points (in 3d space, we would simply see an expanding sphere of light). However as we go closer in, we see that (a) the light is beginning to fall in towards the centre of the black hole, and (ii) it is being pulled away from the light source in the direction circulating around the black hole, by the twisted spacetime metric. Once we go below the first outer horizon in the ergosphere (the light green region), we see that the twist is so strong that the expanding light is pulled completely away from the emitter, in the direction circulating around the hole, ie., the light is being dragged so far by the rotation that it can never get back to the emitter. *However*, it is still not falling irretrievably into the hole - the 'top' of the light sphere is still further out from the black hole than the emitter. Thus, light emitted directly outwards from a point in the ergosphere of a rotating black hole will eventually escape (having probably circulated many times around the hole before it escapes through the outer horizon!). On the other hand, if we look at the emitters inside the lower horizon, we see this is no longer true - now the expanding light-circles are being dragged inexorably downwards, as well as sideways. This inner horizon is the true event horizon.

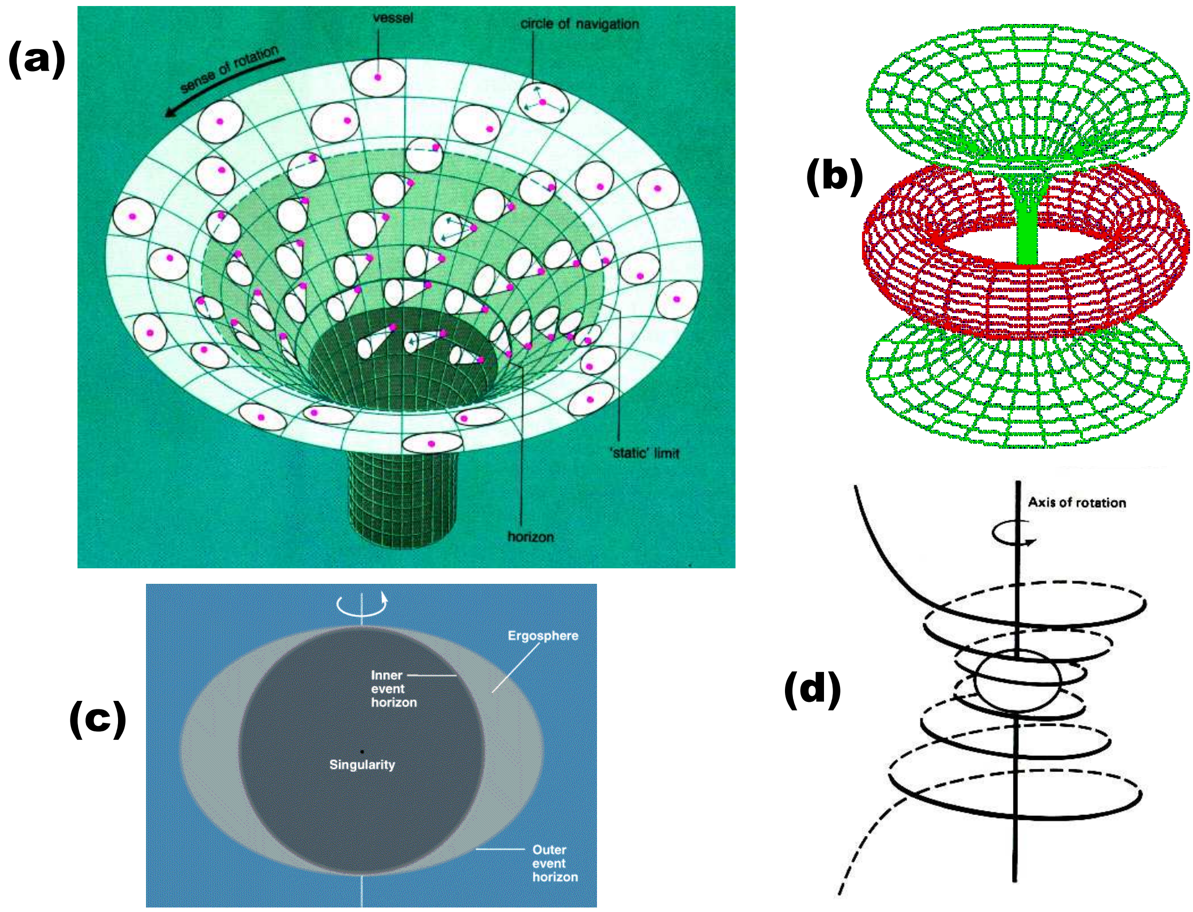

FIG. 3: Rotating "Kerr" black holes. In (a) we show a diagram of what will happen to an expanding spherical shell of light emitted from various points around a rotating black hole. In (b) we show, schematically, the spacetime structure inside the inner event horizon; the 'throat' structure is in green, and the ring singularity in red. In (c) the event horizon structure is shown around the Kerr black hole, with the ergosphere between the inner and outer event horizons; and in (d) we see the path of a light ray passing near a Kerr black hole, parallel to the rotation axis.

Finally, let's look into the very heart of the Kerr black hole. Although this is not relevant for the fate of any object falling into the Kerr hole, the structure of the final 'singularity' in the spacetime is now quite different from before. In the Schwarzschild hole this is just a point in spacetime. But in the Kerr hole it is a *ring*, ie., the spacetime develops infinite curvature at all points on this singular ring. An attempt is made to show this in Fig. 3(b). Recall that in the Schwarzschild black hole, we have a single point singularity in the 4-d spacetime; moreover we could visualize this in a 2d analogue of the 4d spacetime, where the singularity is the point in the 2-d 'sheet' where the stretching and the curvature of the sheet geometry becomes infinite (we show this by stretching it downwards to a point). However, it is not possible to visualize the full 4d geometry of a Kerr black hole in any 2d analogue. The best we can do is actually think of a kind of 3d analogue, in which we imagine 2d analogues at each point in the 3d space. This is what is done in Fig. 3(b), for 2 different points in the Kerr spacetime; the 2d analogue surfaces are shown in green and red.

We find some very curious results. First, let's imagine that we are coming into the black hole down the axis of the black hole (ie., along the line perpendicular to the equatorial plane discussed in the last paragraph). Then, at any point inside the inner event horizon on this line, we see a spacetime that is the 4d generalization of the green 2-d surface in Fig. 3(b). This spacetime is bizarre - we see that it looks as though there is an entry and an exit - it looks like a sort of 'throat'. How can this be? We have already seen that once one goes inside the inner event horizon of a Kerr black hole, one cannot escape. So what does this mean? The answer is extraordinary - if we follow this path we can re-emerge from the black hole, outside the outer event horizon - but in what is mathematically a different space, indeed, it can be thought of, in a certain sense, as an alternate universe. If we then 'dive back in' to the black hole, again along the rotation axis, we can come out again into our own universe - but *in the past.* We have accomplished a 'time-like loop', making a circuit which allows us to go back into the past. There is a superficial similarity here with what we found for a wormhole - but note that the Kerr black hole is a perfectly stable object, unlike the wormhole, and one does not have to discuss whether or not it will collapse, without negative mass-energy density to keep it open.

Now suppose we come into the black hole off the rotation axis. Then we will find ourselves in the region of the 'ring singularity' - the 2d spacetime analogue has the geometry shown in red in Fig. 3(b). This is a genuine singularity, just like the one at the centre of the Schwarzschild black hole. We can actually circulate around it (at least we can imagine doing so mathematically), as well as going through it (eg., when we go down the rotation axis).

These results are very counter-intuitive - indeed, much effort has been put into investigating such time-like loops in this geometry, and in other geometries which have them, to see whether there is some other principle which forbids them. It is safe to say that there are still many unanswered questions about such geometries, and may physicists simply refuse to take time loops seriously. In the case of the Kerr geometry, it is known that the internal geometry, below the inner horizon, is unstable to perturbations, and this gives another reason for ignoring these features of the system. However the region of spacetime outside the inner horizon is a different story, for it is believed to be a completely general description of the spacetime geometry outside the event horizon, no matter what may be going on inside. Hence the practical importance of the Kerr black hole - it probably describes almost all of the black holes in the universe.

It would be beyond the scope of these notes to discuss all the interesting things that can happen in the region of a Kerr black hole. One is this - that an object going into and then re-emerging from the ergosphere can in principle exchange energy and angular momentum with the black hole. This is remarkable, for it means that one can imagine a 'Penrose process' in which such an object actually causes a decrease in the mass of the black hole, at the same time taking large amounts of energy from it. Incredibly, this energy can be as much as 46% of the rest mass/energy (in units where $E = mc^2$) of the object which goes through the ergosphere. Thus we have in principle a s very efficient way of emitting large amounts of energy from a black hole. As we will see later, many of the most powerful processes in the universe are poweed by rotating black holes, and this mechanism is very likely relevant to their power generation.

B: BLACK HOLES in the UNIVERSE

As we have mentioned earlier, the views of astrophysicists towards General Relativity and its more exotic features have evolved enormously in the last 50 years. Curiously, the main reason for this has not been theoretical - most astronomers only learned about the work of people like Oppenheimer, Penrose, Zeldovich, Hawking, etc., after they were forced to. Even some of the theorists needed to be made to believe that what they were doing was relevant to the real world. It is remarkable to read no less a physicist than Feynman saying the following in 1963:

"*There is a certain irrationality to any work in gravitation, so it's hard to explain why you do any of it....But since I am among equally irrational men, I won't be criticized I hope for the fact that there is no possible practical reason for making these calculations.*"

R.P Feynman, *Acta Physica Polonica* **24**, 697 (1963) (from a conference talk in July 1962).

In view of what has happened since then, it is hard to see what Feynman was apologizing for (although he was at that time more interested in understanding quantum gravity). In fact, the purely theoretical investigations made in the early 1960's have borne fruit beyond what any of these early workers might have imagined (except perhaps for Zeldovich). In what follows we will survey some of these remarkable developments, which have completely transformed astrophysics. We begin by discussing briefly how stars live and then end their lives, with massive stars exploding in supernovae, to leave behind either neutron stars or black holes, and smaller stars leaving behind white dwarves. We then go on to look at the supermassive black holes that apparently lie at the centre of all galaxies. Some of these, like the one in our own Milky Way, weigh in at only a few million solar masses. Others are far larger, and they utterly dominate their host galaxies, and even vast regions of space well beyond them. They also create massive disturbances, which are visible to us all the way across the universe.

All of these objects require General Relativity for their description (as well as a healthy dose of quantum mechanics, particularly for white dwarves and neutron stars). All of them, except for white dwarves, were predicted theoretically long before they were discovered by astronomers. And yet, in spite of this, astronomers were initially very sceptical towards the application of these ideas, to the discoveries that began to unroll, one after another, in the 1960's. In what follows I explain a little about what we now know, and some of how we came to this understanding.

B.1 STELLAR and SUPERNOVA REMNANTS

The first place that one can look for black holes is in the carcasses of stars, once they have lived their lives out. However to appreciate what is being done here, we need to first learn a little about stars, and stellar systems. We will then be able to see how a very small number of them , at the end of their lives, are capable of producing black holes with masses of order 3-10 times that of the sun.

B.1(a) STARS: THEIR LIVES and STRUCTURES

It is sometimes stated that our sun is an 'average' star, as stars go - a yellow dwarf, utterly insignificant compared to the galactic searchlights that would dominate the appearance of the Milky Way as seen from outside. Stars come in an enormous variety of colours, luminosities, shapes, and sizes. Rather like fish in the sea (at least before we started to overfish), or plants on the earth, their numbers are dominated by small and very ordinary looking objects. However, the sun is slightly more than average; an 'average' star in the Milky Way is actually an "orange-red dwarf", with a mass roughly half that of the sun but a luminosity perhaps 30-40 times less. It is also smaller, with a diameter roughly 2/5 that of the sun, and cooler, with a surface temperature of roughly 4000 K, instead of the solar value of $6,000$ K. If we replaced the sun by such a star, the earth would be a very different place - the temperature would fall to 120 K (ie., 120^o above absolute zero, or -170^o C, only 30^o above the temperature at which oxygen liquifies)), and the daylight would be much dimmer and redder, roughly like what we see in late afternoon with the sun low in the sky.

Even this desolate picture fails to convey how faint most stars are. To get an idea of this, we can look at the 100 nearest stars to our sun - the "local neighbourhood". These stars are all less than 20 light years from the earth. Well over half the stars in this sample are dim 'red dwarfs', with luminosities much less than even our 'average' orange-red dwarf, ranging between one thousandth and one millionth that of the sun; the faintest of these would look fainter than the moon if placed where the sun is now. In fact, of these 100 stars, only 3 are significantly more luminous than the sun (these being Sirius, which is 23 times more luminous, Altair, which is 11.2 times as luminous, and Procyon, which is 7.5 times as luminous). Of the rest, there are 9 with luminosities similar to that of the sun (ranging from 1.7 times as bright to 1/3 as bright); and the 6 faintest stars have luminosities ranging from 250,000 times less than the sun to 1.2 million times less. This is not to reckon with the 8 "brown dwarfs" so far discovered in this small neighbourhood (see below).

We can think of this another way. The sun has a life expectancy of roughly 13 billion years, of which 5 billion have already elapsed; but our 'average' orange-red star will live for perhaps 200 billion years, and the faint red dwarves which dominate the galaxy will live for hundreds or thousands of *trillions* of years.

Another key difference between the sun and the typical star in the Milky Way is that most stars are not solitary - they are members of multiple star systems. Most commonly these are binaries, but systems of up to 6 stars can be found within a few hundred light years of the earth. In fact, amongst the 100 nearest stars to our sun, fully 60 are in multiple star system (there are 19 double stars, 6 triple star systems, and one quadruple system). Moreover, from what we know of the mechanisms involved in stellar formation, almost all of these star systems will have planets, again of all shapes and sizes. The sun itself has 8 planets, and perhaps 100,000 planetoids (the best-known of which is Pluto). The largest planet in our system is Jupiter, with 11 times the diameter and 318 times the mass of the earth (but only one thousandth the mass of the sun), and with a retinue of nearly 100 satellites (of which 4, the Galilean satellites, are as large as small planets). But we now know that a significant fraction of ordinary stars have planets far larger than Jupiter, as much as 20-30 times the mass of Jupiter. It is virtually certain that all stars are surrounded by a variety of bodies, ranging from millions of comets, asteroids, and planetoids, up to in some cases massive planets far larger than Jupiter. In fact we expect that these planets will range in mass up to 85 Jupiters (ie., roughly 1/12th that of the sun), at which point low-level fusion reactions can begin in their cores, and they become 'brown dwarves'; extremely faint objects whose surface temperature would be similar to that of a domestic fireplace.

Actually, from all this we see that by typical stellar standards, our Solar System is not terribly interesting - there is only one star, and the planets are actually quite small and few in number. Suppose, however, we cast our net farther out. Then, just as with fish in the sea, we find that our local environment gives no hint of what lies in the vaster realms of the galaxy. To help in understanding all of this, it is useful to look at what is called a "Hertzsprung-Russell diagram" (or "HR" diagram") for stellar populations - this is shown in Fig. 4(a).

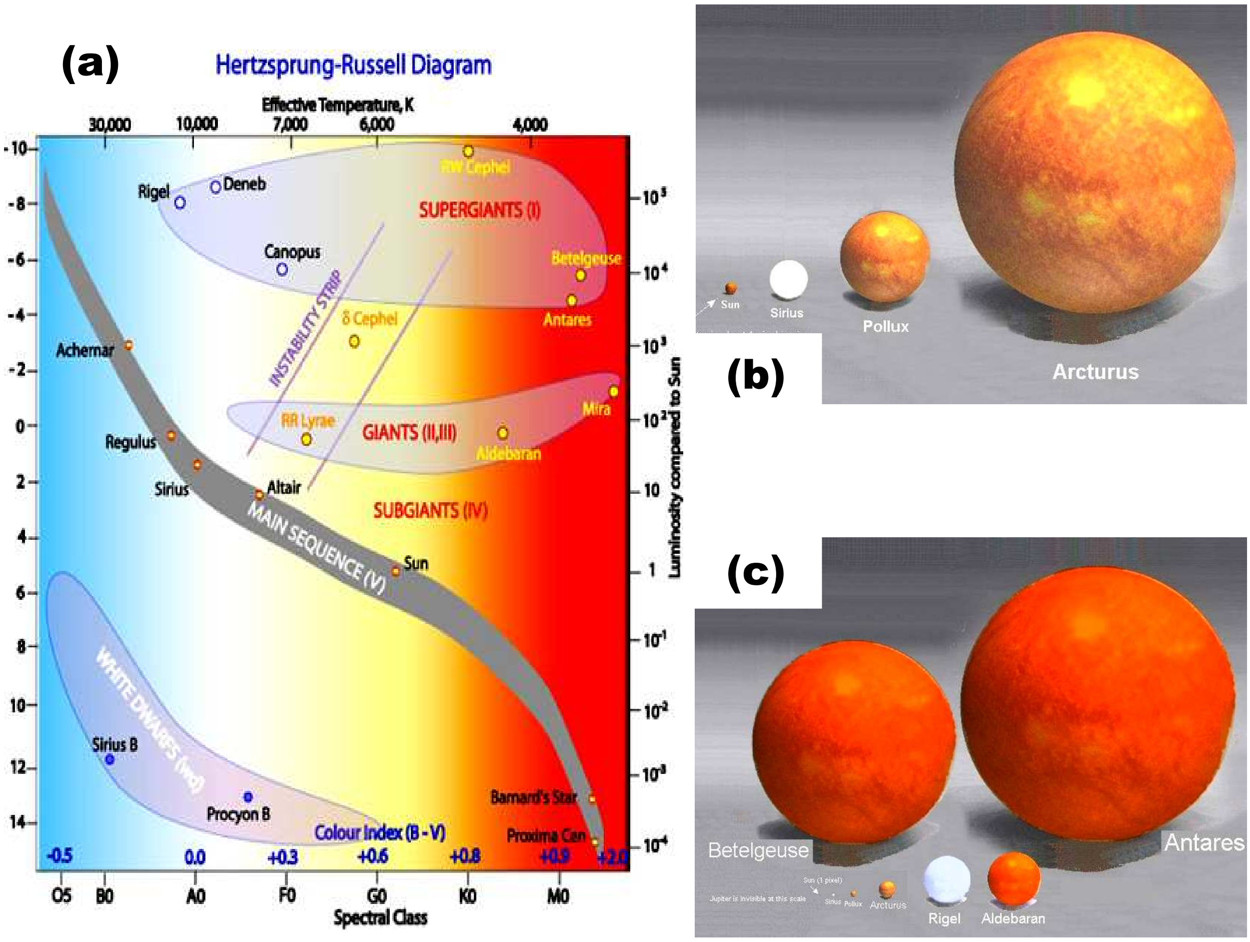

FIG. 4: The structure of stars. In (a) we show the famous 'Hertzsprung-Russell' diagram, which depicts the luminosities of stars (vertical axis) as a function of their temperatures/spectral types. The luminosity is shown measured as compared to the sun (right-hand scale), and in terms of 'absolute visual magnitudes' (left scale). The surface temperature is shown at top, and the spectral type is shown in the bottom scale. In (b) we see the relative sizes of some main sequence and red giant stars - the sun is the smallest shown, at bottom left. In (c) we see some supergiant stars, compared to the orange giant Arcturus (very small orange ball, below Betelgeuse).

The HR diagram shows what kinds of stars are possible. There is a very long strip of stars running diagonally from top left to bottom right - the "Main Sequence". The vertical axis (see scale at right) shows the luminosity of the stars, varying from 1 million (ie., 10^6) times the sun at the top to less than one-ten thousandth (ie., 10^{-4}) at the bottom. We see that the luminous main sequence stars are all very blue and hot, with surface temperatures as high as $50,000$ K and luminosities as high as nearly 10^5 suns (ie., 100,000 suns); whereas the really dim ones are cool and red, with surface temperatures down to well below $4,000$ K, and luminosities down to less then 10^{-4} suns. Actually, from what was said just above about our local environment, we can see that the diagram shown by no means does justice to the whole range of possibilities - there are many stars in our neighbourhood with luminosities far less than 10^{-4} suns, and surface temperatures down to below $2,500$ K; but such stars are very faint as seen from earth, and only easy to track down when not too far away. In the same way there are some stars even hotter than $50,000$ K; the hottest reach nearly $200,000$ K.

Actually the main thing distinguishing the different main sequence stars is their mass - the hot blue ones are more massive then the cool red ones. What mass a star has when it forms is purely accidental - when a cloud of gas and dust collapses and clumps condense into objects, they can have masses ranging from small asteroids up to far larger than the sun. However many instabilities can occur during this condensation, particularly for large condensations, and so larger objects are much less commonly formed. On the main sequence, a large mass object has a much higher central pressure (because of the increased gravitational self-attraction), and this allows much higher core temperatures, and therefore a higher luminosity - in fact, for much of the main sequence, one finds roughly that the luminosity increases as the 4th power of the mass, ie., that $L/L_{\odot} \sim (M/M_{\odot})^4$, where $L_{\odot}$ and $M_{\odot}$ are the luminosity and the mass of the sun, respectively. Thus a star twice as massive as the sun will have a luminosity roughly equal to 2^4 suns, ie., 16 suns; this is roughly what we find for Sirius, the brightest star in our sky (see the white star in Fig. 4(b)). On the other hand a star 10 times as massive as the sun will have a luminosity roughly 10^4 times greater, ie., ten thousand times greater. Such a huge luminosity will cause the outer parts of the stars to inflate - they are pushed outwards by the sheer pressure of the radiation coming from below.

But then how do we explain the monsters that we can see in Fig. 4(b) and (c)? Some of these are really huge. The largest star shown in Fig. 4(b) is Arcturus (note the image of the sun at the bottom left of this figure). This star has a diameter of roughly 40 suns - if places where the sun is now it would span an angle of 20^o, roughly the apparent size of a basketball seen from a little less than 3 ft., or your the the angle subtended by your outstretched hand if you spread your fingers as ar as they will go. Arcturus is an orange giant, and remarkably, in 7 billion years the sun will look not so different (although a little smaller). But Arcturus is minuscule compared to the red supergiants like Antares and Betelgeuse in Fig. 4(c) (note that Arcturus is hardly visible in this figure, just below and to the right of Betelgeuse). Betlegeuse has a diameter of roughly 800 suns (actually its diameter oscillates in time) and Antares is roughly 1200 times as large. If either of these behemoths was in the place of the sun, we would find ourselves not too far from the centre - the surface of Antares would extend beyond the orbit of Jupiter. These are not even the largest stars we know - for example, ϵ Aurigae B has a diameter of roughly 3,000 times that of the sun. And yet, these are not the most luminous stars in the sky. In spite of its great size, Antares has a luminosity of only about 6,000 suns, and is far outshone by Rigel (the blue-white ball at the bottom of Fig. 4(c)). This is because Antares is cool, whereas Rigel is hot, so that the radiation intensity from its surface is quite massive - Rigel has a luminosity of nearly 100,000 suns. The most luminous stars we see in the sky have luminosities of up to roughly 5 million suns (an example being η Carinae). If seen from outside, it is these bright stars that would completely dominate what is seen - just as they make up most of the bright stars we see in our sky. And yet the supergiants are extremely rare. The 2 nearest supergiants to us are Canopus (the 2nd brightest star in the night sky, only visible in the Southern hemisphere) and Betelgeuse in Orion, the 10th brightest star in the sky. But these are at distances of 310 and 320 light years from us respectively, and there are roughly a million other stars closer to the earth than these two.

The explanation for such colossal stars, and for the existence of stars off the main sequence, is to be found in their life cycles. Almost all stars begin their lives somewhere on the main sequence (with the vast majority, of low mass, starting in the 'red dwarf' region, down at the bottom right of the HR diagram). But towards the end of their lives, they undergo a dramatic transformation, which takes them off the main sequence. What happens then depends entirely on their initial mass, as we will now see.

B.1(b) The DEATHS of STARS

As we have seen, almost all stars begin as a condensing cloud of gas and dust, which collapses under its own gravitational attraction, until the central regions reach a high density (and a very high temperature, produced by the heat generated as all the matter collapses inwards). This temperature is high enough, if the mass is large enough, to initiate nuclear fusion in the core. Now, once these thermonuclear reactions switch on, the star will have a lifetime determined almost entirely by its initial mass. This is fairly obvious - a hot fast-burning star like Rigel, even though it has some 20 times the sun's mass, is burning up fuel at a rate 100,000 times higher - so the sun should live roughly 5,000 times longer. As we saw, the sun has a life expectancy of roughly 13 billion years, so a reasonable guess for Rigel's lifespan is just a few million years. On the other had a really faint red dwarf, with a mass less than 1/10-th that of the sun, might have a luminosity a million times smaller - it will go on sedately burning for perhaps a hundred thousand times longer than the sun (ie., for over a thousand trillion years!).

But eventually all good things will come to an end, for any of these stars, and we are faced with the question - what happens when their fuel begins to run out? The answer to this turns out to depend very much on the mass, and we can distinguish 2 main cases.

The fist case involves stars with masses up to roughly 8-10 times that of the sun. Let's consider the sun as an example. It is is now 5 billion yrs old, with a core temperature of 14.7 million degrees; and it will live another 8 billion years. In about 6 billion years it will have slowly expanded to a slightly larger size, and will have perhaps 3 times its present luminosity. It will have finished most of its H fuel, except for the region near the surface, and much of the He formed from the H by fusion as well. However deep within the sun, the 'Carbon cycle' of nuclear fusion reactions will have started, in which 3 He nuclei fuse to form a C nucleus. Its structure will be much as shown in Fig. 5(b). The core temperature will have considerably increased from what it is now - as H and He run out, the core will contract until the temperature rises to the point where the Carbon cycle can begin in earnest. This rise in temperature will not only cause the sun to begin expanding and become more luminous, but allow He and He in the out core regions to burn as well. We see a 'shell structure' develop, in which the temperature and density fall as one proceeds outwards. The heavy V=Carbon is produced in the centre, and stays there, because it is more dense. As He is exhausted in the core, the burning zone must expand outwards, and it can only do this if the core contracts further, heats up more, and allows the He regions further out to join in the C cycle. Thus the luminosity rises to maybe 100-200 times the present level, and the outer regions will balloon out to form an orange giant, similar to the picture we saw of Arcturus in Fig. 4(b).

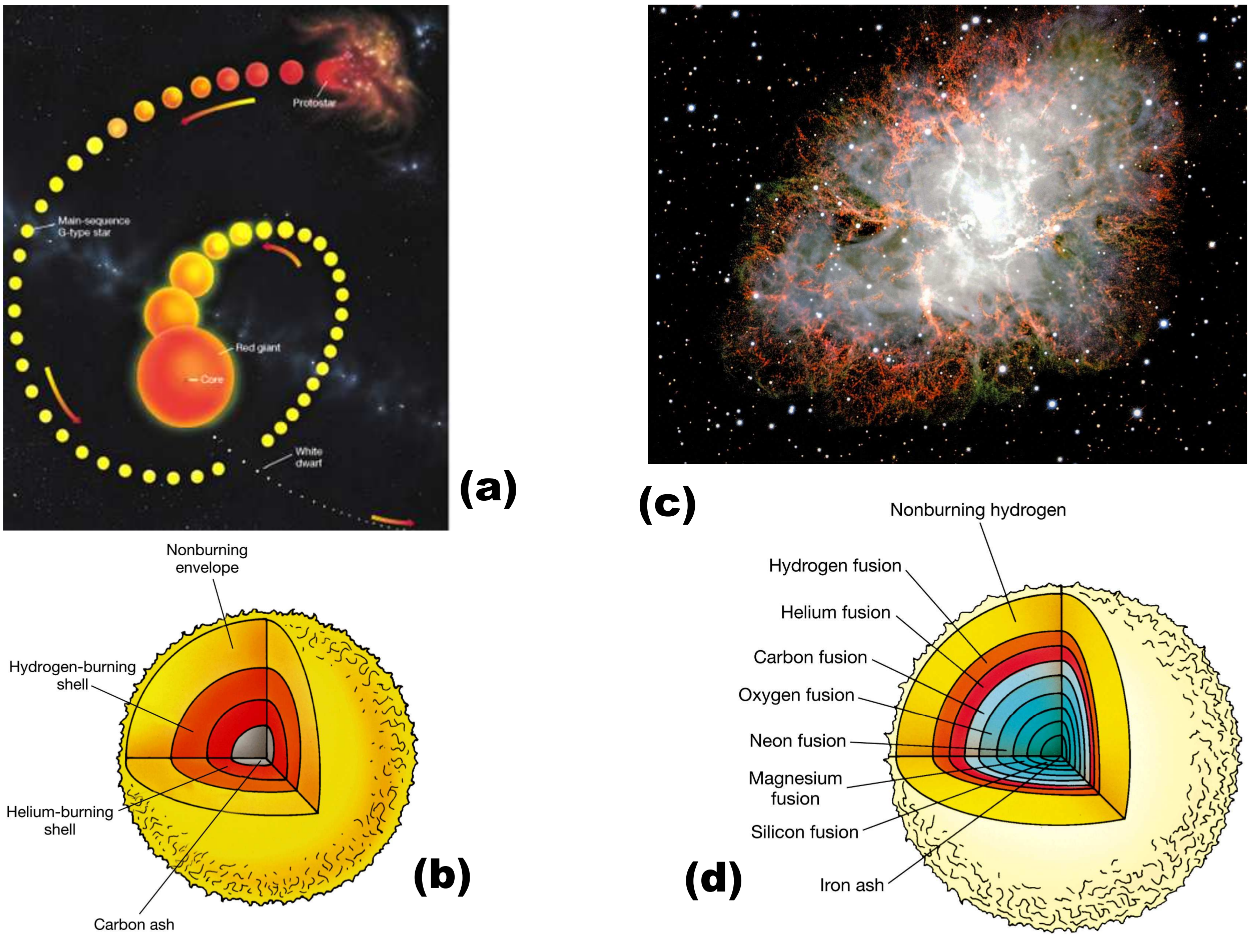

FIG. 5: The lives of stars. In (a) we see the life-cycle of a star similar to the sun, with 'snapshots' taken roughly once every 250 million years - the star begins at top right as a protostar, and then finishes at bottom right as a white dwarf. In (b) we see the shell structure of this same star not long before the orange/red giant phase begins. In (c) we see the Crab nebula - this is how a massive star (of mass greater than roughly 10 suns) ends its life - as a supernova. In (d) we see the shell structure of such a star not long before the supernova.

However, with a star like the sun, this is about as far as things can go. To burn the Carbon, by higher fusion interactions, requires much higher energies and temperatures, and the sun is simply not massive enough to provide these - if the temperature did rise to such levels in a core contraction, the resulting radiation would simply blow the outer layers away. In fact, with many main sequence stars more massive then the sun, this is what happens when the fuel stars to run out completely - the star attempts to 'jump start' higher temperature core reactions by having a core contraction, but succeeds only in blowing off bits of its outer atmosphere. By reducing the mass of the outer layers, this reduces the pressure on the inner core, which then expands slightly, lowering the temperature, and shutting off any further Carbon burning - leading to another core contraction. Thus the star can go into a slow pulsation, or a kind of erratic fibrillation, in which it progressively loses mass. All of this is a signal for the end, when finally no more thermonuclear burning can be sustained, and the core begins to shut down. The outer layers slowly collapse inwards, burning more fuel as they go, but eventually there is so little fuel left that the star contracts to a "white dwarf". On astrophysical timescales, this contraction happens quite quickly - it is all over in a few million years.

The white dwarf is an extraordinary object. Its structure can only be understood using quantum mechanics - it has a density roughly a million times that of ordinary solid matter on earth, so that a teaspoonful would have a mass of roughly 10 tons! Thus a typical white dwarf may be only a couple of times the earth in diameter, and yet have a mass up to 1.4 solar masses. That such an object could exist, and that it moreover could have a maximum mass of 1.4 suns, was first understood by the remarkable Indian theoretical astrophysicist Chandrasekhar, way back in 1931! Chandrasekhar simply applied ideas from the then recently discovered theory of quantum mechanics, and added results form special relativity, to get his results (which at the time caused great controversy). What actually happens in a white dwarf is that the atoms in it collapse under the great pressure of the stellar mass, until what is called the internal 'degeneracy' or 'zero point' pressure of the electrons, acting outwards, is capable of withstanding this inward gravitational pressure. In quantum mechanics you will learn that whenever anyone tries to compress a quantum state to a smaller volume, it will resist with a pressure, and this pressure increases very rapidly as the volume decreases.

The white dwarf is initially quite hot, and very low-level fusion can continue in it - but eventually after a few billion years it will fade into what we call a 'black dwarf', essentially invisible to the outside universe. This is the fate that eventually awaits our solar system.

But what now of more massive stars? Here things proceed differently, because now the mass of the overlaying layers of the star is sufficient to hold it together when the inner core contracts and heats up. Thus we can get higher and higher fusion processes occurring, as heavier and heavier nuclei are made from the lighter ones. The resulting structure is shown in Fig. 5(d). As one penetrates deeper and deeper towards the core, the ever increasing temperature allows fusion to produce ever-heavier nuclei, and we get a 'wedding cake' spherical structure. As the ligher nuclei fuse to heavier ones, exhausting the light fuel inthe core, the star approaches gradually to a point where the supply of heavier and heavier nuclei is exhausted. And this exhaustion can happen very quickly at the end. Thus, a star having an initial mass of 20 suns will spend 10 million years on the main sequence, burning H in its core. However, provided it doesn't lose too much mass by blowing off its outer envelope, it will then spend only one million years burning up its core He, and only 300 years burning its Carbon. During this time, an initially blue-hot massive star may expand its outer envelope to enormous sizes, creating the red supergiants we saw above. As fuel continues to run out, things begin to accelerate incredibly, as the central core temperature and the rate of thermonuclear burning both rise to enormous values, in a desperate attempt by the star to stave off total fuel exhaustion. Near the end, the central temperature rises up to roughly 3 billion degrees, causing the fusion rate to acccelerate to incredible values. The exhaustion of Oxygen nuclei takes only 200 days, and Silicon burning only 2 *days*!

Finally things come to an end, for 3 reasons. First, fusion has to stop with Fe nuclei - all heavier nuclei require energy to be made form lighter nuclei, and so making them will actually suck energy out of the core, rather than producing more energy. A second and even worse problem is that at these colossal temperatures, the photons produced by the thermonuclear reactions start to cause the heavy nuclei like Fe or Si to disintegrate into smaller nuclei - and suddenly all the energy that was liberated by the fusion now has to be paid back (and is paid back, as all the high-energy photons are absorbed by these 'photodisintegration reactions', leaving only much lower energy photons behind). Third and worst of all, the high temperatures allow reactions to proceed in which neutrinos are produced - and neutrinos hardly interact with ordinary matter, and so begin to stream out of the central core, carrying huge amounts of energy with them. The exit of both high-energy photons and neutrinos means that the central core temperature very suddenly drops.

The final result is that in the space of a just a few seconds, the entire central core suddenly finds itself with no fuel and a sudden drop in temperature. Only one things can then happen - the core collapses, and the outer layers of the star then begin to collapse inwards as well, since there is no longer anything holding them up. In the space of perhaps 20-60 secs, depending on the size of the star, the entire mass of the star simply begins to 'free fall' inwards, continuing until the central core reaches densities of roughly $10^{14} - 10^{15}$ times that on earth. This is the density of atomic nuclei, so dense that the whole of Grouse Mountain would now collapse to a sugar lump in size (but still with a mass of perhaps 10-20 billion tons). All the nuclei have been crushed together, and at the end of this precipitous collapse we end up with a dense fluid of neutrons, with the protons and electrons forced together to form neutral matter. But the collapse then stops - in fact, the quantum degeneracy pressure of the neutrons themselves finally stops the inward rush, and there is then a huge 'rebound' effect: the inner core explodes back outwards, with a massive shockwave propagating out to meet the outer parts of the star, which are still falling inwards.

This is the beginning of what we call a supernova. The energies involved are colossal: when the light from this explosion finally penetrates through the incoming matter (heating it in the process to very high temperatures and initiating fusion in the unburnt outer layers), we see a sudden brightening of the star (in the space of a few hours) to huge luminosities - the brightest supernovae can shine for a few weeks with the luminosity of 10 billion suns, a sizeable fraction of the output of an entire galaxy! And yet, incredibly, this is only a tiny fraction of the total energy output - for in the first few tens of seconds of the core rebound, almost all of the energy is leaving the core in the form of invisible neutrinos, rather than EM radiation.

Supernovae occupy a crucial position in the life of a galaxy. In the early stages of the Milky Way, it was composed almost entirely of H and He. As we have seen, elements up to C can be made in the cores of stars of up to 10 solar masses, but these cores never see the outside worlds unless something completely destabilizes the star. But a supernova empties itself almost inside out, apart from the very central core regions, and so the expanding supernova cloud (like the one in the Crab nebula, 6000 light-years distant: this is the remnant of an explosion that was seen in 1058 AD, as a very bright star in the sky, by Chinese astronomers - see Fig. 5(c)). Thus almost all of the heavier elements in our galaxy were released into the interstellar medium by supernovae. Moreover, a supernova, by propagating a shock wave into the gas clouds in this medium, can initiate collapse of this cloud, at the same time 'seeding it' with the heavy elements it has released. When the cloud contracts to form a new stellar system, these heavy elements end up both in the new star, and in the disc of planets and planetoids around it. Planets like the earth, and everything on its surface, are thus formed from material which was created eons ago in the core of a massive star, and ejected in a supernova. We see that the matter we ourselves are made from was entirely formed in a long-dead massive star; in this sense we are indeed stardust.

But what is left behind after the explosion? This is where we can finally find the connection to black holes. For using similar ideas to those of Chandrasekhar, but this time incorporating General Relativity, physicists beginning with Oppenheimer realized that there were only 2 possibilities available to the supernova remnant. By far the most likely is that it will settle down to form a neutron star, which is initially spinning very rapidly, but which soon slows its rotation, and gradually cools down. We now know that the maximum possible mass of a neutron star is roughly 3 solar masses, and it is of course a very strange object. Such a star would have a diameter of only about 20 km, but the gravitational fields around it are so large that one has to use General Relativity to describe the system. The first neutron star to be found was in 1967, by Bell and Hewish, who noticed that a stellar object was giving off very rapid pulses of radio waves (30 times a second). We now know of thousands of such 'pulsars'; the pulses are caused by the rapid spinning of the systems, and what we see is emission from both radiation and high-energy particles, as the 'pulsar beam', emanating from the polar regions, of the pulsar sweeps past us. The fastest pulses have a period not much more than a thousandth of a second - the pulsars are spinning very rapidly when they are formed.

Thus, for a supernova remnant of mass less than 3 suns, we end up with a stable final state. But what if the mass is larger? Then, according to General Relativity, nothing - not even quantum degeneracy pressure - can stop the final collapse to a black hole. Before the discovery of pulsars, and their rapid explanation in terms of neutron stars, such ideas were scarcely given credence by astronomers. But pulsars forced the issue, and soon the hunt was on to find signs of such stellar-sized black holes. And it did not take long before the first candidate was found.

B.2: MASSIVE BINARY X-RAY SYSTEMS and BLACK HOLES:

We have seen above that the end product of stellar evolution is one of two extremely strange objects. In the case of a star with initial mass less than roughly 10 suns, we get a white dwarf, with a diameter a little larger than the earth, and a maximum mass, the Chandrasekhar mass, of 1.41 suns; However for a more massive star, we in all likelihood get a neutron star, of maximum mass of roughly 3 suns, and diameter perhaps 20 km. Any supernova remnant that was heavier than this should have given a black hole. And so astronomers needed to find the signatures of such an object in the sky.

B.2(a) X-RAY OBSERVATIONS

The problem was (and still is) - how do you see one? After all, it is black - it is not emitting any radiation! The solution to this problem came in what should have been an obvious way. We have seen that most stars end up in multiple star systems - so one can then ask - what happens to, for example, a close binary, once one of the stars has died? Obviously there will be many such systems out there, and so it seems obvious that this is an important question.

The problem was forced to the surface by observations in the period from 1964-71, of 'X-ray sources', the best-known of which is the 'Cygnus X-1' system. The "X" designation signifies that the object is an important X-ray source. Because the earth's atmosphere blocks all X-rays from reaching the ground, it was not until 1962 that the first astronomical observations came in, made from sounding rockets launched into sub-orbital space by the Americans. More and more sources were observed, but what immediately distinguished Cygnus X-1 were the observations of short-time fluctuations in its output. In 1970 NASA launched the Uhuru satellite from Kenya ("Uhuru" is the Swahili word for 'freedom'), and it quickly identified 336 different X-ray sources, and carried out extensive observations of some of these (notably Sco X-1, Cen X-3, Vela X-1, and Her X-1). Finally, in 1971, Cygnus X-1 was found to be a radio source, which allowed earth-based observers to identify its exact position: it was found to be the previously catalogued star HD 226868, in a cluster of stars called Cygnus OB2, lying some 6,100 light years from the earth. Almost immediately it was then found that we were dealing with a double star system, and that both stars were very massive. A photo of the area of the sky where it was found is shown in Fig. 6(a). Note that HD 226868 is not the bright star in the field - this is η Cyg - but is one of the many fainter stars close by.

The rapid variability of the X-ray emission from Cygnus X-1 (which has now been seen on time scales of 1 millisec), plus the fact that both stars were revealed to be very massive, made it seem very likely by 1971 that one was dealing with a black hole. At the same time, it was being discovered that other strong X-ray emitters were also in binary systems - and it began to emerge that some of the stars in these had very large masses as well. Current estimates of the mass of the Cygnus X-1 emitter vary between 11-20 solar masses, with a value of 14.8 favoured; and the companion blue supergiant has a mass of at least 20 solar masses. The 2 stars orbit each other every 5.6 days, at a distance of roughly 35 million km, in a near circular orbit. By 1973 it seemed fairly clear that Cygnus X-1 was a very good candidate for a black hole, but there was no real proof of this, nor a good explanation for everything that was being seen. In 1975 Stephen Hawking and the Caltech astrophysicist Kip Thorne made a well-known bet, which is described by Hawking as follows:

"*This was a form of insurance policy for me. I have done a lot of work on black holes, and it would all be wasted if it turned out that black holes do not exist. But in that case, I would have the consolation of winning my bet, which would win me four years of the magazine Private Eye. If black holes do exist, Kip will get one year of Penthouse. When we made the bet in 1975, we were 80% certain that Cygnus X-1 was a black hole. By now [1988], I would say that we are about 95% certain, but the bet has yet to be settled*"

S. Hawking, in "*A Brief History of Time*", Bantam books (1988)

A few years later, Hawking conceded the bet, as the evidence became overwhelming. Rather than go through the subsequent history, which depends to a great extent on evidence from other X-ray sources, as well as very extensive theoretical analysis, let's move now to the current picture of these systems. An artist's view of Cygnus X-1 is shown in Fig. 6(b). What we see here is believed to be fairly typical of what are called "accreting X-ray binaries'. On the right of the image we see the large supergiant, HD 226868, in the system - and trailing from it we see a streamer of hot gas, which is being sucked into the black hole, Cygnus X-1, at left. The material that is given up by HD 226868 forms an "accretion disc" around Cygnus X-1, which we see spiralling into Cygnus X-1, and the physics of such discs is actually very complex. Indeed, in the last 40 years much theory and observation has been consecrated to understand how matter, impinging on a rotating massive object, eventually finds its way down the gravitational potential well to the object - we summarize this below. Finally, in Fig. 6(b), we see how a pair of jets emerges from Cygnus X-1 along the axis of rotation of the black hole - these jets are believed to be generic features of such systems.

B.2(b) The PHYSICS of ACCRETION DISCS

We are all familiar with what happens to an object orbiting the earth - the very rarified gas at high altitude causes a frictional drag, even far above what is normally considered to be the limit of the earth's atmosphere. It is for this reason that satellites and other human-made junk very slowly lose energy, so that their orbits decay, and they gradually descend to the limits of the upper atmosphere. From then their lives are very limited - they very soon burn up in a fiery descent to the earth's surface. The frictional drag is thus responsible for the loss of energy, which allows the object to spiral slowly in to the earth.

The same basic idea applies to the accretion of matter around a massive dense object (white dwarf, neutron star, black hole), except there are 3 key differences, viz.:

(i) the gravitational fields are now massive, requiring general relativity for their description. They are so strong that one of these bodies can literally dredge its companion star for material; the outer envelope of the companion is rendered unstable by the gravitational attraction of the dense star (white dwarf, neutron star, or black hole). This envelope then balloons out to fill a region of space around the companion star, called the "Roché lobe". From there the matter and gas in the envelope begins to slowly funnel into the region around the dense star, and enters into rapid orbit around this star, in an "accretion disc". Because of friction, the matter then starts to spiral into the dense star. In this way the dense companion can actually cannibalize the companion star, eventually destroying it.

(ii) the rotation rates of these systems are extremely high - both the accretion disc, which will be orbiting really fast because of the strong gravitational fields, and also the stars themselves. This applies particularly to neutron stars, and by implication to any black holes. The velocities involved are significant fractions of the velocity of light, and the accelerations are colossal - matter is torn to shreds, into electrons, nuclei, and even sub-nuclear particles, and highly accelerated charges emit massive amounts of radiation. As the matter spirals in, it can emit an enormous amount of energy away from the central attractor, equivalent to a considerable fraction of its entire rest energy (ie., of the energy mc^2).

(iii) In many cases, the magnetic fields around these systems are quite enormous - and moving charged particles are funneled along the field lines. Because the star is rapidly rotating, this can have also the 'whiplash' effect of accelerating the charges to incredible energies. The magnetic poles will usually be roughly aligned along the rotation axis of the dense star or black hole, and so perpendicular to the plane in which the accretion disc lies. Because of

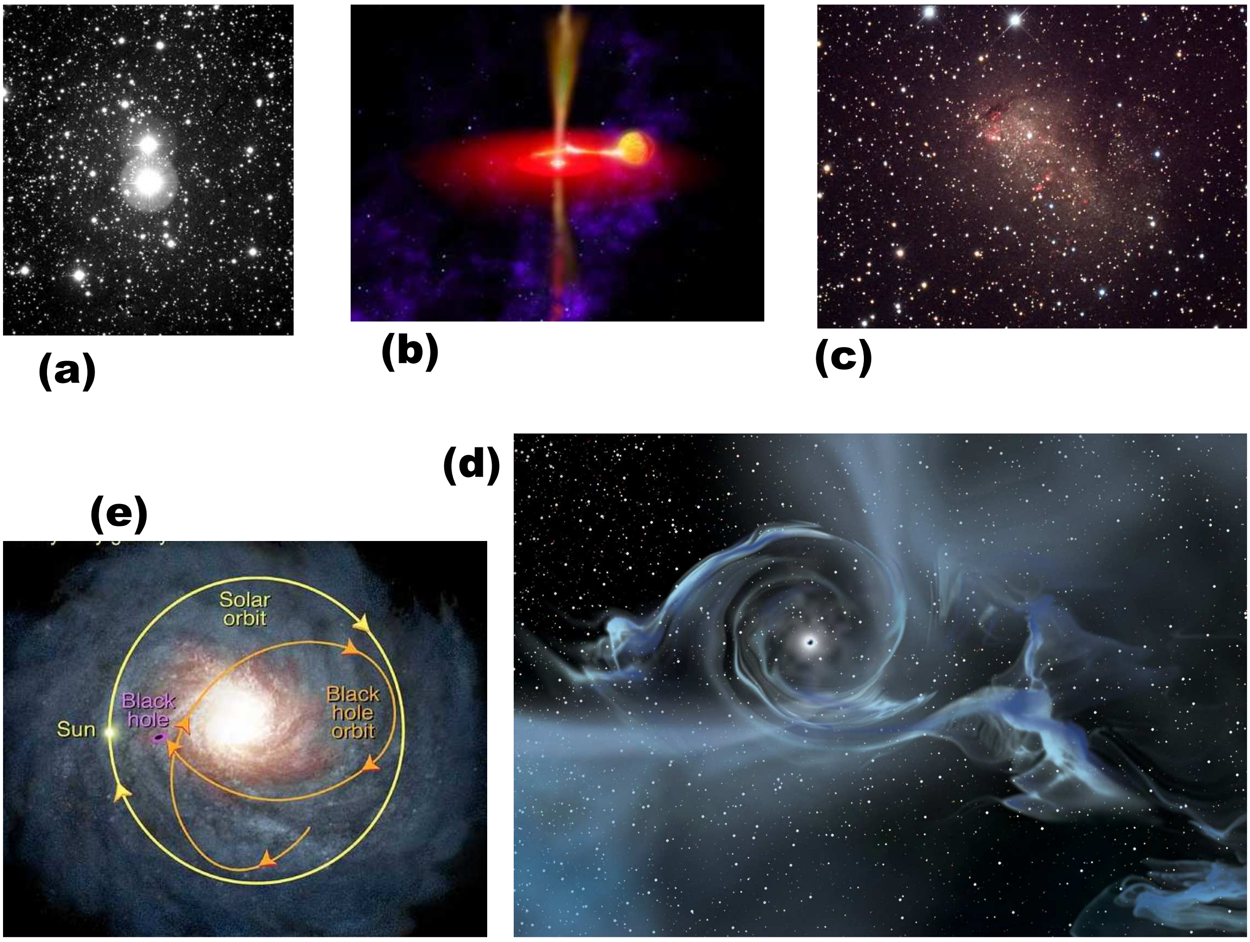

FIG. 6: Black Holes in binaries: the remnants of supernovae. In (a) we see the star field of Cygnus X-1, whose actual form is shown in the artists representation in (b), with an accretion disc around the black hole at left. In (c) we see the irregular galaxy IC-10, and (d) shows a painting of what the black hole IC 10-X1 in this galaxy might look like. In (e) we see the orbit in the Milky Way of GRO J1655-40, a rapidly moving Black hole binary system.

this, it is much easier for radiation and high-energy particles to escape along the directions of the poles, and so 2 high-energy 'jets' emerge from the dense star along these directions. This is where most of the emission from the dense star/black hole is concentrated.

Thus we see that accretion discs are rather dramatic affairs, looking like some giant rotating firework, shaped like a Catherine Wheel, except that not only are sparks and radiation flying outwards, they are also spiralling inwards.

Naturally, when all this matter spirals into a white dwarf or a neutron star, severe consequences can result when it crashes down onto the surface. The energies are so high that much of the emitted radiation from the 'crash landing' is at very high energies, indeed, in the form of X-rays - and this is of course ow we see these systems. One can also get 'X-ray bursters', and 'X-ray novas', where accumulated material arriving onto the surface of a neutron star suddenly undergoes explosive fusion. Still more dramatic is a Type Ia supernova, which occurs when the matter accumulating onto a white dwarf from its accretion disc finally causes the mass of the star to exceed the Chandrasekher limit. When this happens, the star must suddenly collapse to the density of a neutron star. However, unlike in the case of the supernovae described earlier, in which the dramatic events occurring inside the core regions of a supergiant star are shielded from the outside by the infalling outer layers of the star, now the fireworks are all happening near the surface - the white dwarf, and the neutron star it collapses to, are already tiny. Thus, paradoxically, type Ia supernovae are actually visually brighter than the usual Type II supernovae.

But, we may ask, what happens if in some way one of the dead stars finds itself with a mass greater than 3 solar masses, so that not even a neutron star can hold up. We now see why the exist of a companion star is so important. In the first place, if a solitary star explodes in a supernova, and then collapses to a black hole, it will be essentially invisible once the supernova cloud has dissipated (which may take only 100,000 years). So even if there are lots of these out there, we cannot detect them - whereas if they are part of a binary system, they make themselves visible by sucking matter out of the companion star. And in the second place, even if the collapsed star is not initially large enough to form a black hole, it can get there by accumulating more mass from the companion star.

And indeed this seems to be what has happened in most of the cases now known where we can say with near certainty that we are dealing with a black hole in a binary system. Certainly Cygnus X-1 is one of these, but we now have even better candidates. One is in the irregular galaxy IC 10, shown in Fig. 6(c), which lies roughly 2.4 million light years from the earth - it is a satellite of the Andromeda galaxy M31. This X-ray binary is very happily oriented so that the orbits of the 2 masses around each other are presented edge-on towards us. This means that every 34.9 hours (the orbital period) the bright supergiant companion passes in front of the X-ray source, and eclipses it. It also means that we can learn in some detail, by knowing the orbital characteristics of the pair, what are their masses - and there is now strong evidence that the mass of the X-ray emitter must be between 24 and 32 solar masses. It has been clearly stripping the bright supergiant of its envelope, and in fact this companion is highly luminous and a little unstable, so that just the stellar wind from it is enough to supply the black hole with its dietary needs. An artist's impression of this system appears in Fig. 6(d).

Finally, we may ask - how likely is it that our own solar system might pass close to one of these rather nefarious objects? Obviously they are all far away from us now - but are any likely to approach us? To see how such a thing might happen, it is useful to look at Fig. 6(e), which shows the path of the X-ray binary GRO J1655-40 in its orbit around the Milky Way. We see that by galactic standards, it will pass not so far away from our own system, proceeding in its roughly circular orbit. The timescales are long - the sun takes some 230 million years to accomplish its orbit - but we see that in perhaps 25 million years, GRO J1655-40 will make its closest approach to us. But one needs to realize the scales involved here. The sun's orbit is 26,000 light years in radius, and at this distance form the centre, a typical nearest neighbour interstellar distance is 5-7 light years. The closest approach of GRO J1655-40 may be several thousand light years, and at this distance, even if the companion for some reason explodes in a supernova, it will be no more obvious to us than the Crab supernova was in 1058 AD.

However, the black holes in X-ray binaries are by no means the largest that can exist. We now turn to objects that exist at the centres of many galaxies, which in the most extreme cases can be classified as true galaxy-killers.

B.3 SUPERMASSIVE BLACK HOLES at GALACTIC CORES

One of the most remarkable discoveries of the last 20 years in astrophysics has been that at the centres of most galaxies there reside truly colossal massive objects, which can only be black holes - these have been dubbed 'supermassive' black holes. You should supplement the following discussion of these objects, by looking at the course slides.

B.3(a) The MILKY WAY BLACK HOLE

It is convenient to begin by looking at the evidence for the existence of a massive object at the centre of our own galaxy, the Milky Way. There is no way we can look directly at the central regions of the Milky Way using optical instruments - some 26,000 light years separate us from the galactic centre, and much of this is filled with quite dense clouds of gas and interstellar dust (not to mention billions of stars). The 'extinction factor' of the light from the centre, caused by this dust, is roughly 10^{10}, ie., only a fraction of one part in 10^{10} (one part in 10 billion) manages to get through at optical wavelengths. However, the dust and gas are largely transparent at radio wavelengths, and this allows us to image the radio wave emission from the central regions of our galaxy.

The results are shown in Fig. 7(a). This is a remarkable image, produced by radio telescope observations using 2 widely separated radio telescopes to produce a single image. Although the intensity of the final image depends on the total area of the 2 telescopes, and so does not depend on how far apart they are, the *resolution* (ie., the angular width of the smallest object or detail that can be resolved - roughly speaking, the 'pixel size') increases in proportion to the separation. Thus Fig. 7(a) is looking at an extremely small area of the sky, in the region of our galactic centre. By looking at how objects move in this region we can actually determine exactly where the centre is (the centre being the point around which everything is orbiting, ie., the "bottom of the gravitational potential well"). The 'radial motion' of objects (ie., their motion towards or away from us) is easily found by looking at the Doppler effect in their spectra; and, incredibly, we can see their 'sideways motion', transverse to the radial direction, in real time, by watching how the positions of things change over the years. This is seen in the 3 small inserts to Fig. 7(a), where the motion of objects in the very small region of "Sagittarius A*" is seen, by taking images at different times (this region is labeled "Sgr A*"; here "Sgr" is the symbol for the constellation of Sagittarius). In Fig. 7(a) we see not only the fuzzy images of gas and dust, emitting radio waves, but also stars; and both of them are changing in time.

Using these images, we can produce the blow-up in Fig. 7(b), which plots the motion of several stars very close to Sgr A*. We see that they move in orbits, around one common central massive object. The star with the smallest such orbit is called 'S2', and its orbit is shown in Fig. 7(c). To get an idea of the scale of things here, notice the

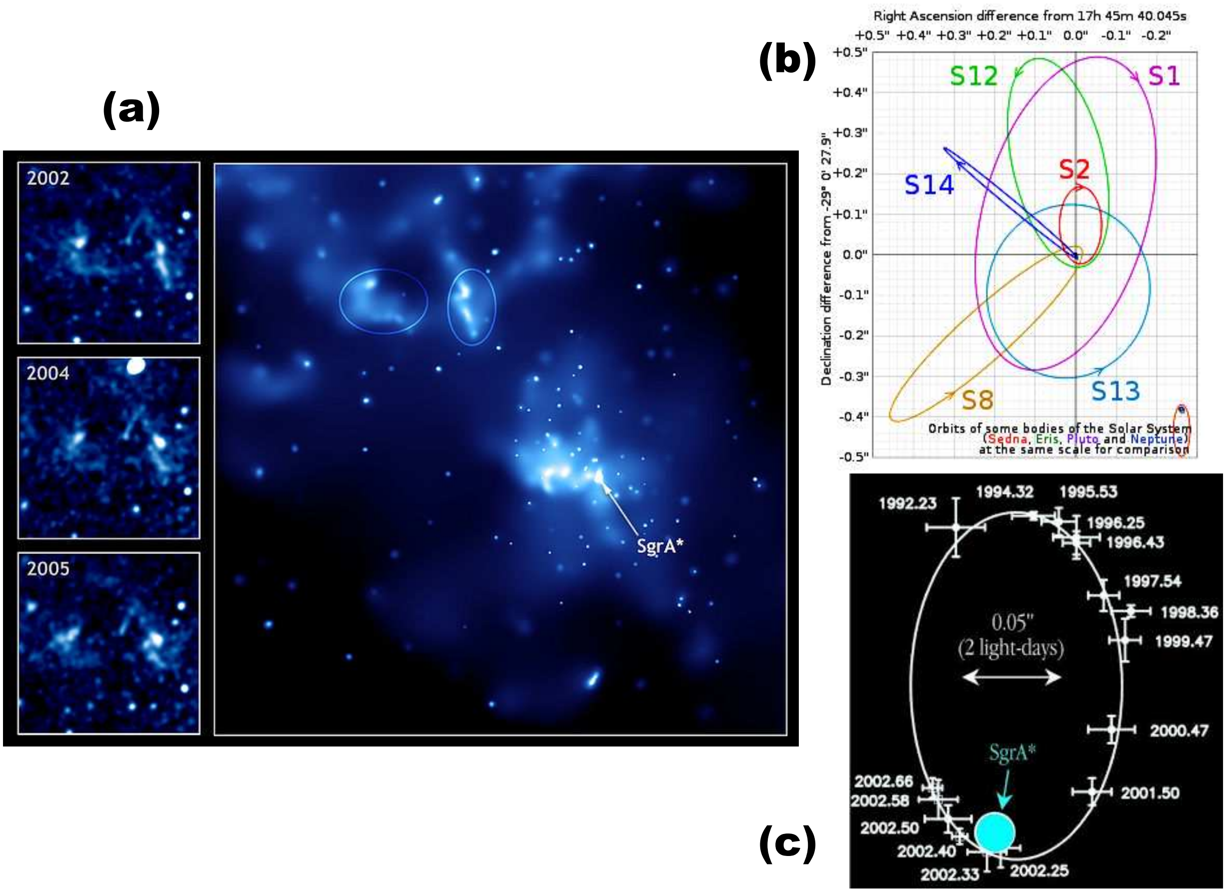

FIG. 7: The Sagittarius A supermassive black hole at the centre of the Milky Way, 26,000 light years away from us. In (a) we see a photograph taken at radio wavelengths of this region; the insets show how the central region changes rapidly in time. In (b) we see the orbits of some of the stars in close orbit around the central mass; and in (c) we see the orbit plotted for the closest such star, S2, between 1992 and 2002. The distance between the 2 arrow-tips in (c) is 0.05" of arc in the sky, corresponding to a real distance at Sgr A* of 2 light-days (ie., 50 billion km).

the distance between the two arrow-tips, in the double-headed arrow shown in the image, is 0.05" of arc in the sky - this is roughly the angle subtended by a dime at a distance of 1 km, or a small sand grain at 100m distance (ie., quite impossible to resolve with the naked eye). And yet at the distance of Sgr A*, it corresponds to a real length of roughly 50 billion km, ie., 330 times the distance from the earth to the sun. or 9 times the distance of Pluto from the sun. We see that the star S2 is moving extremely fast in its orbit as it gets close to Sgr A*; in fact it reaches a maximum velocity of 12,000 km/sec at its closest approach. This is extremely fast - at this velocity one would traverse the diameter of the earth in a single second. Only an enormous mass could be responsible for this, and in fact it is calculated that the mass of the central object in Sgr A* is roughly 4.3 million solar masses (corresponding to a Schwarzschild radius of roughly 13 million km, ie., a black hole with an event horizon having a diameter of 26 million km). This is not all - for extremely accurate observations of Sgr A* have now been made using 'VLBI' techniques (NB: VLBI = 'Very Long Baseline Interferometry' - here one separates the radio telescopes by very large distances, and looks at the interference between the 2 signals). These have found that the size of the central emitting object is only 44 million km in diameter - hardly larger than the Schwarzschild radius! Now we recall that the black hole itself is not emitting - what we are seeing is radiation emitted by matter in the process of falling through the event horizon, and getting ripped apart as it does so. This matter is emitting from just outside the event horizon.

The region being immediately affected by the Sgr A* black hole is, right now, very small. This situation may change next year (2013), since a small gas cloud (the cloud G2) is moving very rapidly towards the black hole, and is expected to be torn apart by it at the time of its closest approach in late summer 2013, when it will be only 36 light hours (ie., roughly 26 times the radius of the earth's orbit) from the black hole, not much farther than Neptune is form the sun. If this happens, an accretion disc will form around the black hole, leading to a significant amount of emission over subsequent years, particularly X-rays. Such an event would be extremely interesting to astronomers - indeed it would provide us, over a period of perhaps days or months, with a firework display at close had, which will probably afford us a much better understanding of what is really going on in some of the most distant objects in the universe (for which see below).

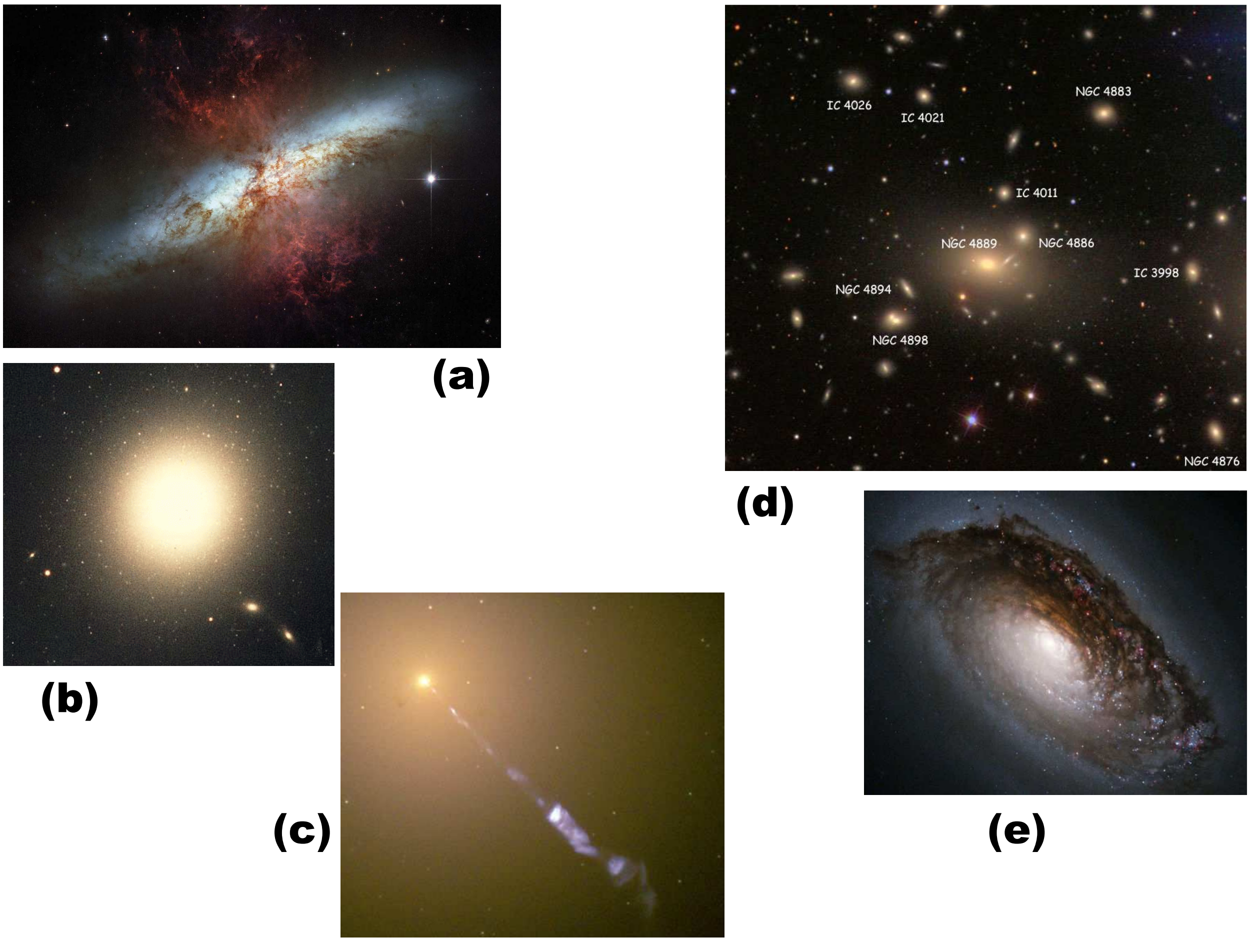

FIG. 8: Some galaxies having active nuclei and supermassive black holes. In (a) we see a composite image of the M82 galaxy, in optical and hydrogen-alpha wavelengths. In (b) we see the giant elliptical galaxy M87, and in (c) we see the relativistic jet at its core. In (d) we look at the central regions of the Coma cluster, 320 million light years away; near the centre is NGC 4489, shown in (e) at much larger scale.

All of these observations make it very clear that we are dealing with a supermassive black hole at the centre of the Milky Way. And yet it turns out that by cosmic standards, this is a rather insignificant supermassive black hole. It only strongly affects a small neighbourhood around itself, and right now it hardly seems to be interacting much with its tenuous gaseous environment - there seems to be no large accretion disc of material around it, probably because the black hole has cleaned this out, like a giant vacuum cleaner. To see really more dramatic events than this, we have to go to other galaxies. There are of course perhaps a trillion galaxies visible to us in the largest of modern telescopes, and the closest of these are visible to the naked eye (The two 'Magellanic clouds' are satellite galaxies of our own Milky Way, at 180,000 light years distance, and are visible as small cloudy patches on a dark night in the Southern Hemisphere; and the giant spiral galaxy M31, at a distance of 2.4 million light years, is visible as a small smudge in the northern constellation of Andromeda, on a dark night). We now believe that all of these have supermassive black holes - the one in M31 has a mass of some 40 million suns. In Fig. 8(a) we see another nearby galaxy, at a distance of nearly 12 million light years - this is M82, which looks as though some kind of explosion has taken place in the core at some time ago. This galaxy is a member of the class of 'starburst' galaxies, because its cental core is involved in a phase of very rapid star conception and birth, indicating that the gas and dust in this region is collapsing very rapidly - in fact there are more stars being born in the small central region each year, than in the entire Milky Way. M82 also has a supermassive hole, whose mass is estimated at 37 million solar masses. The current consensus is that this black hole, as well as the tidal gravitational forces from the nearby large galaxy M81, are causing the burst of star formation, by stirring up the central regions, and so causing much of the gas and dust to collapse into compact star-forming clouds. Thus we see one way that it is possible for black holes to exercise a large effect on the galaxies they live in.

B.3(b) GIGASOLAR MASS BLACK HOLES

It turns out that what we have seen so far is nothing! The supermassive black holes in the Milky Way, or M31 and M82, turn out to be really puny compared to some of the monsters that exist in the further reaches of the universe. These are really frightening in their size. In Fig. 8(b) and (c) we see images of the monster galaxy M87, situated at 54 million light years from us in the heart of the Virgo supercluster of galaxies. This galaxy, as previously mentioned, has a mass of some 2.7 trillion solar masses; the visible portion is a deformed sphere, of diameter 130,000 light years, but this is only 1/6-th of the mass of the whole galaxy, which extends out nearly 500,000 light years from its centre. Now at the very centre of this galaxy we see a very high-energy jet of material, shown in Fig 8(c), which is some 7,000 light years long. The energy of this massive jet is huge: it is moving at nearly the velocity of light, and any stellar system in its path has been very severely disrupted (certainly nothing resembling life could survive such an onslaught). A closer look at this system has revealed massive shock waves passing through the entire galaxy, and into the medium outside it - these are betrayed by their very high-energy X-ray emission. These shock waves have, over the life of the galaxy, heated up and driven much of the gas towards the outskirts of the galaxy, and thereby seriously impeded the formation of stars in the later life of M87. Closer to the centre, very large quantities of gamma-ray radiation - of extremely high energy - are being emitted, and the intensity of this radiation has been seen to fluctuate quite markedly, changing even over periods as short as a few days.

The only possible explanation of such observations is that there is a supermassive black hole at the galactic centre, so powerful that it has probably extinguished life over most of M87, and completely changed the evolution and morphology of the system. And indeed it has been possible to track this black hole down, by its effect on the motion of objects near the galactic core - it turns out to have an enormous mass, some 6.6 billion times the solar mass (ie., roughly 5% of the mass of the entire Milky Way). Such a black hole will have an event horizon some 40 billion km in diameter, 4 times the size of the solar system (as defined by the orbit of Pluto). And yet this monster, in a galaxy which is really very near to us by cosmological standards, is not even the largest one yet seen. The honour for this goes to the supermassive black hole at the centre of the galaxy NGC 4883 in the Coma cluster, some 320 million light years distant (see Figs. 8(d) and (e)). This is another very large galaxy, and the mass of the central black hole, discovered in 2011, is currently estimated to be some 21 billion solar masses.

This subject is one that is evolving rapidly - we may expect to see more such monsters discovered in the near future. But the obvious question is - what is creating them, and how do they get so big? This is a topic of current research, and it takes us to the next topic - that of active galactic nuclei and quasars.

B.3(c) QUASARS and ACTIVE GALAXIES

A growing suspicion, that the centres of galaxies might harbour all sorts of interesting activity, began a long time ago amongst astronomers. Already in 1943, Seyfert had obtained optical evidence that in some galaxies, the central cores were in a rather excited state, and by the 1950's Ambartsumian was strongly pushing the idea of 'active galactic nuclei', ie., that the central regions of galaxies could be extremely violent places, and that the processes therein could exercise a large influence on the evolution of these galaxies. However, for a long time, these ideas were treated as somewhat marginal - most galaxies seemed very normal.

As noted already, things began to change in the 1960's on many different fronts. The discovery of quasars in 1963, and the gradual realization that some quite extraordinary mechanism must be working in these if they really were distant objects, was of key importance, as was the discovery of more and more 'anomalous' features in galaxies, even apparently quite ordinary ones. Much of this change occurred because new observational tools became available - first radio telescopes after the war, and then, as it became possible to send satellites up carrying telescopes of one kind or another, the whole range of the EM spectrum became accessible. Of crucial importance was the availability of observations in the X-ray and even gamma-ray wavelengths, since such radiation can only be emitted by matter under very extreme conditions, in which energies are very high indeed. A whole variety of objects became visible, including BL Lac objects (galaxies names after the radio source BL Lacertae, originally thought to be a star but now known to be a galaxy some 2 billion light years away), and various other types of 'radio galaxy' emitting huge amounts of energy.

We now know that all of these objects have in common the existence of a very powerful mechanism at their cores, driving the emission of copious amounts of radiation. They are often accompanied by evidence of extremely violent events, from massive jets like that seen in M87, to vast explosions, far larger than a supernova.

By far the most interesting example of such active galaxies are the quasars. When these were first discovered they were a real mystery - they looked like stars, and moreover were clearly rather small, since their light output sometimes

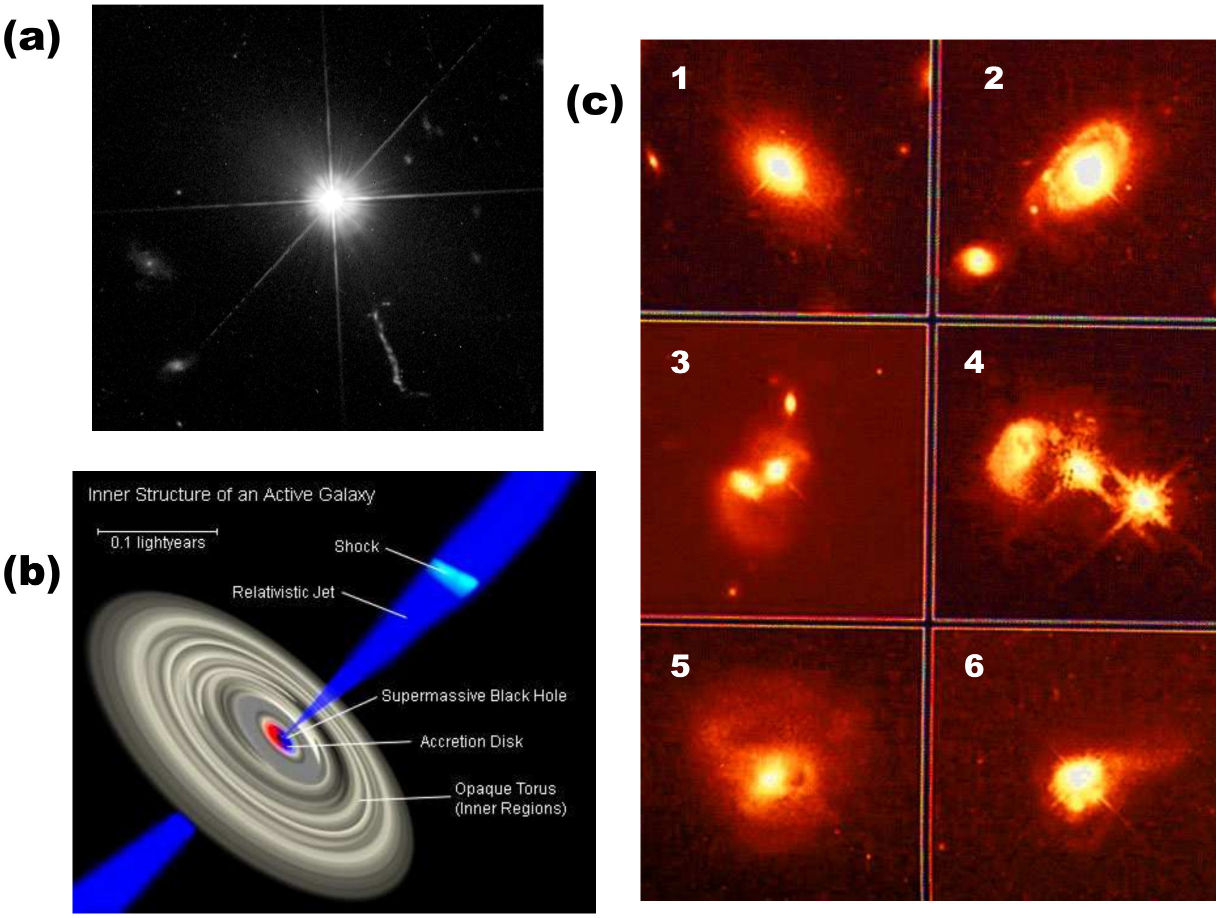

FIG. 9: Images of quasars. In (a) we see the famous first quasar ever discovered, 3C273, at a distance of 3 billion light years. In (b) a depiction of the central regions of an active galaxy or quasar is shown. In (c) we see images of 6 different quasars, at varying distances; these are (1) PHL909, in an elliptical galaxy; (2) PG 0052+251, in a spiral galaxy; (3) PG 1012+008, in a binary galaxy; (4) 2 colliding galaxies, with the quasar IRAS 04505-2958; (5) quasar IRAS 13218+0552; and (6) quasar 0316-346, trailing gas from a previous galactic collision.

fluctuated strongly in times of less than a day. In fact, the only way that they could be distinguished from ordinary stars was by their radio output - they emitted very strongly at radio wavelengths. However, their redshifts showed them receding at huge velocities, usually exceeding 100,000 km/sec. This would place them at distances of many billions of light years, and moreover would give some of them a luminosity hundreds of times greater than even a giant galaxy. This seemed so incredible that many astronomers were unconvinced that the redshifts reflected the real distance of the objects.

Eventually the observational evidence began to tell (there are now over 100,0000 quasars known); but far more importantly, it began to dawn on astronomers that there was a very natural way in which one could have an enormously powerful radiating object of such small size - if one had a black hole in the centre, it would clearly be able to influence its local surroundings on short time scales. And eventually, as more and more powerful telescopes became available, with greatly improved optical systems (including 'adaptive optics'), the observational evidence that quasars really were parts of host galaxies began to make it clear that this was the only realistic point of view. As examples of more recent observations, we can look at Fig. 9(c), which show a whole variety of such objects, in all cases surrounded by their host galaxies. Even the original quasar, 3C273, the first to be identified, has had its galaxy imaged (the galaxy is much fainter than the quasar), and it has been possible to look at the massive jet emerging fromt he core. This is seen in Fig. 9(a); it looks similar to the jet emerging from M87, but this one is an incredible 120,000 light years long, considerably larger than the galaxy itself!

The problem with all this is of course that even if one accepts that the centre of quasars is dominated by some very large black hole, one still has to explain such enormous quantities of energy are being produced. The most luminous quasars are radiating energy at a rate equal to tens up to thousands that of an entre galaxy (ie., many trillion times the output of the sun), and all of this energy is being produced in a tiny central region, in some cases no more than a few light days across! This energy output is equivalent to the conversion of roughly a thousand solar masses into pure energy each year.

The picture we now have of this began to emerge once it was realized that the jets gave us a crucial clue. It was clear that matter in the neighbourhood of a black hole could be devoured by it, but the problem was - how could the matter be induced to fall out of its orbit around the black hole, and why would this produce so much radiated energy? The answer is that a very rapidly orbiting mass of gas would, through friction and collisions between different parts of the gas, form a disc-shaped cloud around the black hole; and the friction would constantly be transferring energy from the inner to the outer parts of the disc, as the inner parts tried to speed up the outer parts. Consequently the inner parts would rapidly lose energy and fall into the hole, and as they did so, their rapid acceleration (which would tear the matter apart) would release huge amounts of energy - an effect coming straight from General Relativity. Moreover, most of this energy would be ejected or emitted along the axis of rotation, partly because it would be blocked from emerging along the disc plane by the incoming matter. The final result of these ideas, which required considerable theoretical analysis, is shown in Fig. 9(b). The emerging jet, of enormous intensity, is made up of radiation and some relativistic matter, driven so hard that it contains massive shock waves which heat it to extremely high temperatures, enough to emit copious gamma rays.

We have already seen how the presence of a very large supermassive black hole, in the centre of a galaxy like M87, can disrupt the entire galaxy. It will be clear from what we have seen of quasars, and from Fig. 9, that with quasars we are dealing with a whole new level of galactic catastrophe. No quasar is close enough for us to look at the detailed structure of their resident galaxies, but one can surmise that the effect of the central regions on the rest of the galaxy is enough to render it utterly sterile - planets would suffer massive radiation intensities, which would rapidly strip their atmospheres and in all probability finish off the planets after a time. Gas clouds would be driven far from the galaxy, leaving nothing to condense into stars. The picture that emerges from all of this is of a truly violent universe, in which quiet regions, like our own interstellar backyard, seem very tame indeed.

B.3(d) GAMMA RAY BURSTERS

We have just seen that quasars are the seat of unimaginably violent events, which can truly be called 'galaxy killers', in the sense that anything in a galaxy which gets in the way of the jets will be rendered sterile. And yet, quite remarkably, these are still not the most violent objects we know of in the universe. The honours here go to what are now known as "short gamma-ray bursters", and we will finish our survey with these.

Gamma rays, like X-rays, cannot be detected from the earth's surface, since we are protected from them by the atmosphere. Actually they are much more difficult to observe even from space - they are so energetic that it is hard to build any device that can focus them and make images. In one of those stories that reveals much, it turns out that gamma-ray bursters were observed by American and Soviet military satellites long before they were known to astronomers. These satellites were made to look for signs of nuclear weapon fabrication and testing, and instead what they saw, beginning in 1967, was sudden intense flashes of gamma radiation from points in outer space. When the extensive data was declassified and finally made public, astronomers began to examine what was seen and make gamma ray detectors themselves, for use in probes orbiting the earth.

For a long time astronomers had very little information to go on - all they knew was that there were occasional bursts of gamma radiation coming from space, which in some cases lasted just one or two seconds (the 'short bursters') and in other cases up to several minutes (the 'long bursters'). The positions of the bursters in the sky did not seem to coincide with any known nearby objects, and so their source was a mystery. However, in 1997 it finally became possible to both pinpoint the source of one of the bursts, by making optical observations very rapidly after the burst, and to observe the 'afterglow' of the burst, at both X-ray and optical wavelengths. The optical measurements also allowed the taking of spectra, and the identification of spectral lines. What was then found was very shocking - the bursters had very large redshifts in their spectra, making them enormously distant. The shock, as we will see, lay in the power output that this then implied.

The key first observations were made by the Italian-Dutch "BeppoSAX" satellite, which had been designed to measure X-rays over a wide range of wavelengths. In Feb 1997 this satellite detected a gamma-ray burster and was able to quickly point the X-ray telescope towards the source of the burst and detect a fading X-ray afterglow, and also give an accurate position for the source. Within 20 hrs the earth-based Herschel telescope, located in the Canary islands, was able to locate the object optically, and so the first gamma-ray burster (named GRB 970228) was found - the burst turned out to be coming from a very distant galaxy. Shortly thereafter, BeppoSAX located another burster, called GRB 970508, and for this one it was possible to observe it optically within 4 hrs, and get a spectrum from it - it then became clear that the object was extremely distant, over 6 billion light years away.

The importance of these results meant that astronomers have, since then, made great efforts to obtain more rapid information about the bursts. The current state of affairs is illustrated in Fig. 10(a), which shows the NASA 'Swift' satellite, whose sole purpose is to look for gamma-ray bursters, and track down the source within seconds of the

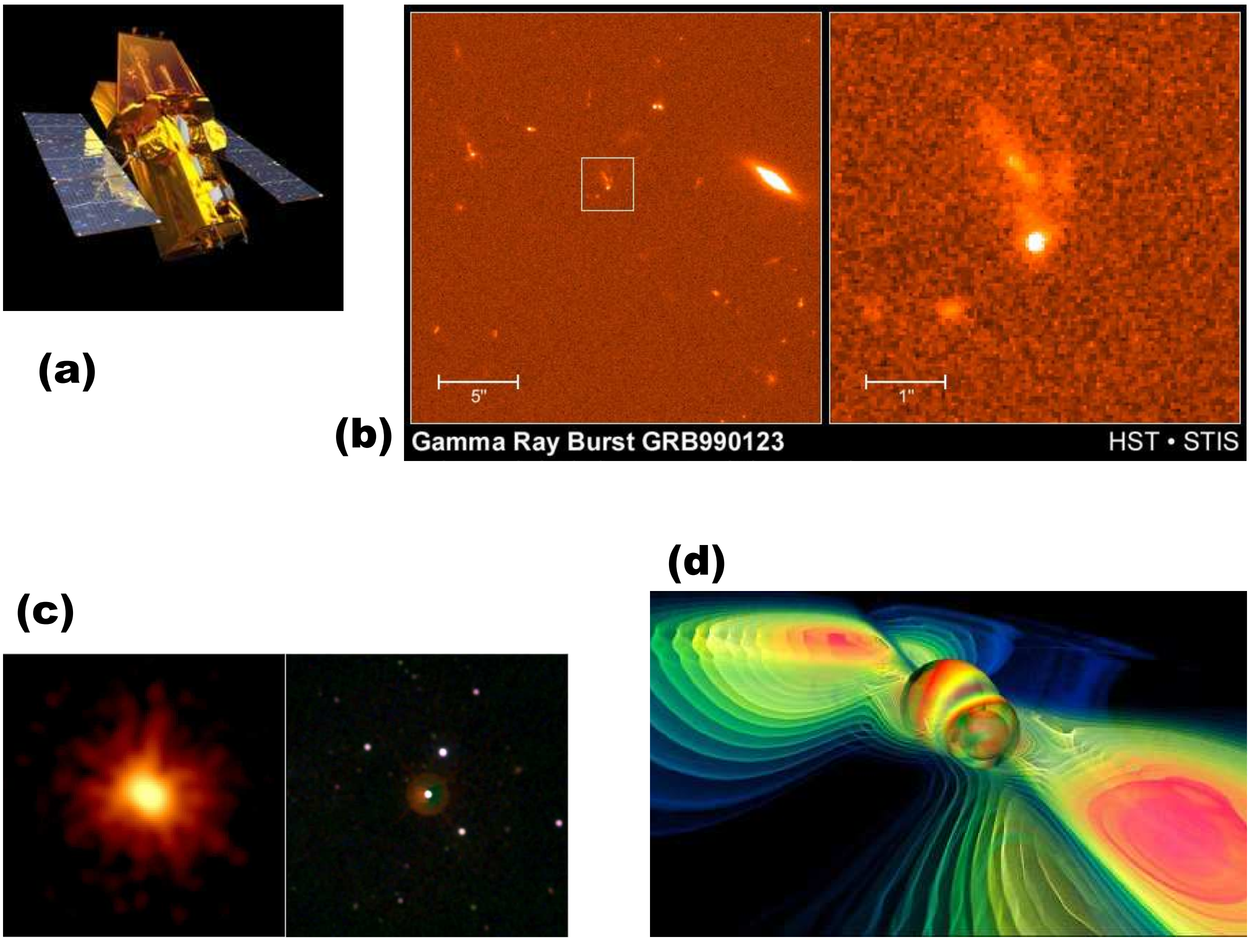

FIG. 10: Gamma-ray bursters. In (a) we see the NASA Swift satellite, carrying gamma-ray, X-ray, and optical telescopes. In (b) we see optical images of the burster GRB 990123, taken with the Hubble space telescope; the right-hand image is a blow-up of the left-hand one, with the angular scale in seconds of arc shown. In (c) we see an X-ray image (left) and an optical/UV image (right) of the burster GRB 080319B, seen in 2008; this was the brightest burster ever seen. In (d) we see one scenario for the a short gamma-ray buster - this shows the emission of gravitational waves from a pair of colliding black holes, with the most intense shown in red.

burst beginning. This satellite carries both a sensitive gamma-ray detector and X-ray and optical telescopes, and is designed so that the X-ray and optical telescopes can be rapidly re-oriented to observe the burster, within seconds of the gamma ray signal being picked up. With this and other probes active, several hundred gamma ray bursts are now seen each year.

To see why these systems are so extraordinary, let's just quickly look at two of them. Fig. 10(b) shows an optical image, taken with the 2.5m Hubble space telescope (this mean that its mirror is 2.5m in diameter). We are seeing the afterglow of the burster GRB 990123, seen on Jan 23rd, 1999. This burster is an example of a long burster: the gamma ray burst lasted some 90 seconds, and the optical signal somewhat longer. The redshift gives a distance of 9 billion light years, more than halfway to the edge of the visible universe - and yet at maximum brightness, the optical burst was visible in binoculars! The Hubble image was taken when the burst luminosity had already faded by a factor of 3 million, allowing the host galaxy to be seen - in fact this galaxy is a double, and appears to be 2 colliding galaxies.

In Fig. 10(c) we see a more recent burster; this is GRB 080319B, seen on March 19, 2008. The image at left is the X-ray image, which was much brighter than the optical image, shown at right. This burster set a remarkable record. In spite of the fact that it was at a distance of 7.5 billion light years (halfway across the universe), it attained such a brightness that it was for a short time *visible to the naked eye!!* It is hard to over-emphasize how astounding this is. This means that at peak intensity, GRB 080319B was optically nearly a *billion* times brighter than a typical type II supernova at maximum brightness. To put it another way: this burster was, at peak luminosity, shining optically with the luminosity of 20 million Milky Way galaxies (and remember that our galaxy is a rather large galaxy, as galaxies go). And, to top it off, most of the emission was not even at optical wavelengths, but instead at X-ray and gamma ray wavelengths. This was another example of a long burster; indeed the object was visible to the naked eye, had anyone cared to look, for roughly 30 seconds.

Short bursters appear to be rather different - a typical short burst lasts for only 0.2 secs, and can be considerably shorter. This indicates that a very small object is responsible, only a few times larger than the earth for the shortest bursts. What on earth could be responsible for such fantastic releases of energy?

We are at a similar stage right now, as far as these bursters go, to where we were in the 1970's as regards X-ray binaries - there are plenty of models, but not enough in the way of clear tests of the models to discriminate between them. To make things more difficult, there seem to be several different kinds of bursters, and it is very likely that the ones we see are associated with different kinds of object. In the first place, theory indicates that the collapse of a neutron star to a black hole (in, eg., an accreting binary), or the collapse of a stellar neutron core to a black hole in a supernova, could produce a powerful gamma-ray burst. Another way in which this can happen is if a neutron star is swallowed by a black hole, or if 2 neutron stars collapse into each other to form a black hole. Still another way, which would produce a more 'drawn-out' gamma-ray burst, would occur of a star was swallowed by a black hole - the star would start to break up well before it went into the event horizon, and so although the core might be swallowed quite quickly, the rest of the star would be swallowed in bits, or as part of an accretion disc.

All of these scenarios all realistic in that the ingredients are already there - we know that the orbits of orbiting binaries will eventually decay, and so the stars will collapse into each other, and we know that this final collapse is very sudden indeed. One thing that is also rather clear is that in many cases, the orbital angular momentum of the systems will be very large, and so much of the radiation will be emitted along jets or beams. Thus the bursters that we see will only be a fraction of the total - others, emitting in directions away from us, will not be nearly as bright. And so in fact we should not have been surprised to see very powerful gamma-ray bursters - much of the physics we already knew implied that they ought to be out there.

Perhaps the most spectacular possibility that has been discussed in this context is shown in Fig. 10(d). For we can imagine the possibility of two black holes themselves collapsing into each other. Since there is no upper limit to the size of a black hole, the masses and energies involved are truly frightening. For, depending on the geometry, a non-negligible fraction of the total rest mass of the two black holes can in principle be converted into pure energy during such a process. This is of course where Einstein's famous formula $E = mc^2$ comes in. To get a handle on the numbers, consider that during the sun's life of 13 billion years, the total energy it radiates will be not much more than a ten thousandth of its total mass. On the other hand, when 2 stellar black holes spiral into each other, a mass of order a solar mass or more might be converted into energy in a tiny fraction of a second! Fig. 10(d) shows the final stages of this - it is in fact a plot of the spatial distribution of gravitational wave energy being emitted by the 2 black holes as they are in the process of eating each other. The actual collapse process is very dramatic indeed, with a massive outpouring of both EM radiation and gravity waves in the final stages (the 2 black holes will move into each other at nearly the velocity of light, under the influence of their enormous attraction, and this will cause a massive and sudden perturbation of the spacetime geometry around them). We are looking at a snapshot of a process whose final stages (where the black holes coalesce and then merge into one) takes only a ten-thousandth of a second for 2 black holes having 10 solar masses each. Notice how the gravitational wave energy is highly collimated - emerging along the axis of rotation of the 2 bodies, as we would expect.

This picture describes the collision of 2 stellar black holes. One can of course envisage, during the collision of 2 galaxies (a not infrequent occurrence), a time when the 2 supermassive black holes at each galactic core end up merging. This process would take longer, since the black holes are much bigger - the merging of 2 black holes of 4 million solar masses (like those at the core of the Milky way) would take 40 secs. But of course the energies are also correspondingly larger. Such events will be rare - more common will be events in which stars or stellar black holes are captured by supermassive black holes in galactic nuclei. However we see that in all these cases, one expects titanic amounts of energy to be emitted in a very short time.

These results, on gamma-ray bursters, apparently take us to the limits of what is energetically possible in the universe, even during gravitational collapse. However, it seems very likely that further revelations are in the pipeline, given the large loose ends in our understanding of what is going on at the cosmological scale in the universe. Most notable of these mysteries is the problem of dark matter and dark energy - why does this not form black holes, or collapse into black holes, or interact in some obvious way with them? Or perhaps it does? We see that there are very still big surprises in store for us.

In the last 40 years the once abstract theory of General Relativity has completely transformed the subject of astrophysics. It has shown us that objects like black holes are not just mathematical curiosities, but are engines driving some of the key processes going on in the universe. These processes may seem very far away from us (many of them are) and perhaps irrelevant to our daily concerns - although they have certainly not been irrelevant to the history of the earth, and will certainly play a role in its future history. Nevertheless, only a century after the discovery of General Relativity, it has opened a door for us to the entire universe - and at the same time, reminded us yet again how small we are, and of how many mysteries are still left to be discovered and solved.