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BLACK HOLES ARE NOT SO BLACK

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Black holes can be defined as the set of events from which it is not possible to escape to a large distance. To understand how a black hole might be formed, one first needs to have an understanding of the life cycle of a star. A star is formed when a large amount of gas, mostly hydrogen, starts to collapse in on itself due to its gravitational attraction. As it contracts, the atoms of the gas collide with each other more and more frequently, and at greater and greater speeds. As a result, the gas heats up. Eventually the gas will be so hot that when the hydrogen atoms collide they no longer bounce off each other but instead merge with each other to form helium atoms. The heat released in this reaction, which is like a controlled hydrogen bomb, is what makes the stars shine. This additional heat also increases the pressure of the gas until it is not sufficient to balance the gravitational attraction, and the gas stops contracting. It is a bit like a balloon where there is a balance between the pressure of the air inside, which is trying to make the balloon expand, and the tension in the rubber, which is trying to make the balloon smaller.

The star will remain stable like this for a long time, with the heat from the nuclear reactions balancing the gravitational attraction. Eventually, however, the star will run out of its hydrogen and other nuclear fuels. And paradoxically, the more fuel a star starts off with, the sooner it runs out. This is because the more massive the star is, the hotter it needs to be to balance its gravitational attraction. And the hotter it is, the faster it will use up its fuel. The sun has probably got enough fuel for another five thousand million years or so, but more massive stars can use up their fuel in as little as one hundred million year, much less than the age of the universe. When the star runs out of fuel, it will start to cool off and so to contract. When the star becomes small, the matter particles get very near to each other. But the Pauli exclusion principle says that two matter particles can not have both the same position and the same velocity. The matter particles must therefore have very different velocities. This makes them moves away from each other, and so tends to make the star expand. A star can, therefore, maintain itself at a constant radius by a balance between the attraction of gravity and the repulsion that arises from the exclusion principle, just as earlier in its life the gravity was balanced by the heat.

However, there is a limit to the repulsion that the exclusion principle can provide. The theory of relativity limits the maximum difference in the velocities of the matter particles in the star to the speed of light. This mean that when the stars got sufficiently dense, the repulsion caused by the exclusion principle would be less than the attraction of gravity. Indian scientist Subrahmanyan Chandrasekhar calculated that a cold star of more than about one and a half times the mass of the sun would not be able to support itself against its own gravity. This mass is known as Chandrasekhar limit.

This has serious implications for the ultimate fate of massive stars. If a star's mass is less than the Chandrasekhar limit, it can eventually stop contracting and settle down to a possible final state as a White Dwarf with a radius of a few thousand miles and a density of hundreds of tons per cubic inch. A White Dwarf is supported by the exclusion principle repulsion between the electrons in its matter. One observes a large number of these White Dwarf stars. One of the first to be discovered is the star that is orbiting around Sirius, the brightest star in the night sky.

It was also realized that there is another possible final state for a star also with a limiting mass of about one or two times the mass of the sun, but much smaller than even the White Dwarf. These stars would be supported by the exclusion principle repulsion between the neutrons and protons, rather than between the electrons. They are, therefore, called Neutron Stars. They would have had a radius of only ten miles or so and a density of hundreds of millions of tons per cubic inch.

Stars with masses above the Chandrasekhar limit, on the other hand, have a big problem when they come to the end of their fuel. In some cases they may explode or manage to throw off enough to reduce their mass below the limit, but it is difficult to believe that this always happened, no matter how big is the star. How would it know that it had to lose weight? Even if every star manages to loose enough mass, what would happen if more mass added to a White Dwarf or Neutron Star to take it over the limit. The problem of understanding what would happen to such a star according to general relativity, was not solved until 1939. A young American, Robert Oppenheimer suggested that there would be no observational consequences that could be detected by the telescopes of the day.

Oppenheimer's work states : The gravitational field of the star changes the path of light rays in space-time from what they would have been had the star not been present. The light cones, which indicate the paths followed in space and time by flashes of light emitted from their tips, are bent slightly inward near the surface of the star. This can be seen in the bending of light from the distant stars that is observed during an eclipse of the sun. As the star contracts, the gravitational field at its surface gets stronger and the light cones get bent inward more. This makes it more difficult for light from the star to escape, and the light appears dimmer and redder to an observer at a distance.

Eventually, when the star has shrunk to a certain critical radius, the gravitational field at the surface becomes so strong that the light cones are bent inward so much that the light can no longer escape. According to the theory of relativity, nothing can travel faster than light. Thus if light can not escape, neither can anything else. Everything is dragged back by the gravitational field. So one has a set of events, a region of space-time, from which it is not possible to reach a distant observer. This region is now called a Black Hole. Its boundary is called the event horizon. It coincides with the paths of the light rays that just fail to escape from the black hole.

The boundary of the black hole, the event horizon, is formed by rays of light that just fail to get away from the black hole. It is like running away from the police and managing to keep one step ahead but not being able to get clear away.

The path of these light rays could not be approaching one another, because if they are, they must eventually run into each other. It would be like someone else running away from the police in the opposite direction. You would both be caught or, in this case, fall into a black hole. But if these light rays were swallowed up by the black hole, then they could not have been on the boundary of the black hole. So light rays in the event horizon had to be moving parallel to, or away from, each other.

Another way of seeing this is that the event horizon, the boundary of the black hole, is like the edge of a shadow. It is the edge of the light of escape to a great distance, but, equally, it is the edge of the shadow of impending doom. And if one looks at the shadow cast by a source at a great distance, such as the sun, he will see that the rays of light on the edge are not approaching each other. If the rays of light that from the event horizon; the boundary of the black hole, can never approach each other, the area of the event horizon could stay the same or increase with time. It could never decrease, because that would mean that at least some of the rays of light in the boundary would have to be approaching each other. In fact, the area would increase whenever matter or radiation fell into the black hole.

Also, suppose two black holes collided and merged together to form a single black hole. Then the area of the event horizon of the final black hole would be greater than the sum of the areas of the event horizons of the original black holes. This non decreasing property of the event horizon's area placed an important restriction on the possible behavior of black holes.

The non decreasing behaviour of a black hole's area was very reminiscent of the behaviour of a physical quantity called entropy which measures the degree of disorder of a system. It is a matter of common experience that disorder will tend to increase if things are left to themselves; one has only to leave a house without repairs to see that. One can create order out of disorder, for example, one can paint the house. However, that requires expenditure of energy, and so decreases the amount of ordered energy available.

The second law of thermodynamics has a rather different status than the other laws of science. Other laws, such as Newton's law of gravity, for example, are absolute law is that is, it always hold. On the other hand, the second law is a statistical law, that is, it does not hold always, just in the vast majority of cases. The probability of all the gas molecules in a box being found in one half of the box at a time is many millions of millions to one, but it could happen.

However, if one has a black hole around, seems to be a rather easier way of violating the second law: just throw some matter with a lot of entropy, such as a box of gas, down the black. The entropy of matter outside the black hole would go down. One could, of course still say that the total entropy, including the entropy inside the black hole, has not gone down. But since there is no way to look inside the black hole, one cannot see how much entropy the matter inside it has. It would be nice, therefore, if there was some feature of the black hole by which observers outside the black holes could tell its entropy; this should increase whenever matter carrying entropy fell into the black hole.

A research student at Princeton named Jacob Bekenstein, suggested that the area of the event horizon was a measure of the entropy of the black hole. As matter carrying entropy fell into the black hole, the area of the event horizon would go up, so that the sum of the entropy of matter outside black holes and the area of the horizon would never go down.

This suggestion seemed to prevent the second law of thermodynamics from being violated in most situations. However, there was one fatal flaw: if a black hole has entropy, then it ought also to have a temperature. But a body with a non zero temperature must emit radiation at a certain rate. It is a matter of common experience that if one heats up a poker in the fire, it glows red hot and emits radiation, too; one just does not normally notice it because the amount is fairly small. This radiation is required in order to prevent violation of the second law. So black holes ought to emit radiation, but by their very definition, black holes are objects that are not supposed to emit anything.

One can understand this emission in the following way: what one thinks of as empty space can not be completely empty because that would mean that all the fields, such as the gravitational field and the electromagnetic field, would have to be exactly zero. However, the value of a field and its rate of change with time are like the position and the velocity of a particle. The uncertainty principle implies that the more accurately one knows accurately one of these quantities, the less accurately one can know the other.

So in empty space the field can not be fixed at exactly zero, because then it would have both a precise value, zero, and a precise rate of change, also zero. Instead, there must be a certain minimum amount of uncertainty, or quantum fluctuations, in the value of a field. One can think of these fluctuations as pairs of particles of light or gravity that appear together at some time, move apart, and then come together again and annihilate each other. These particles are called virtual particles. Unlike real particles, they can not be observed directly with a particle detector. However, their indirect effects, such as small changes in the energy of electron orbits and atoms, can be measured and agree with the theoretical predictions to a remarkable degree of accuracy.

By conservation of energy, one of the partners in a virtual particle pair will have positive energy and the other partner will have negative energy. The one with negative energy is condemned to be a short-lived virtual particle. This is because real particle always have positive energy in normal situation. It must, therefore, seek out its partner and annihilate it. However, the gravitational field inside a black hole is so strong that even a real a particle can have negative energy there.

It is, therefore, possible, if a black hole is present, for the virtual particle with negative energy to fall into the black hole and become a real particle. In this case, it no longer has to annihilate its partner; its forsaken partner in a fall into the black hole as well. But, because it has positive energy, it is also possible for it to escape infinity as a real particle. To an observer at a distance, it will appear to have been emitted from the black holes. The smaller the black hole, the less far the particle with negative energy will have to go before it becomes a real particle. Thus, the rate of emission will be greater, and the apparent temperature of the black hole will be higher. The positive energy of the outgoing radiation would be balanced by a flow of negative energy particles into the black hole. By Einstein's famous eq. $E=mc^2$, energy is equivalent to mass. A flow of negative energy into the black hole, therefore, reduces its mass. As the black hole losses mass, the area of its event horizon gets smaller, but this decrease in the entropy of the black hole is more than compensated for by the entropy of the emitted radiation, so the second law is never violated.

Reference :

[1] Hawkings, S.W., Theory of Everything.