Black Holes, Less Understood Parts of our Universe and our Theories

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Physics is the science of understanding Nature through mathematical formulations and, here understanding means making models, analyzing the model to make predictions, and make observations or experiments of natural phenomena to check the predictions. Once predictions of a model passes this test, physicists claim to understand those phenomena. This modern notion of science and in particular physics was mainly initiated with the seminal works of Galileo Galilei, which was shortly followed by Isaac Newton and is continued to date. According to Newtonian dynamics, we have a notion of ``force'' which quantifies how particles and systems interact and ``see each other''. Therefore, one in principle knows everything about the dynamics of a system once one can formulate the forces acting on the system and its constituents. Since the time of Newton, physicists have tried to formulate forces. In fact the first and still very much challenging force of Nature was formulated by Newton himself, *the gravity*. Newtonian gravity is the force which is exerted on any mass, like us, the Earth, the Sun or any other object, and is proportional to the inverse-square of the distance between the two bodies. (It seems that Hooke, Wren and Halley, who were contemporaries of Newton, had independently discovered this law, but it is largely known as Newtonian gravity.) Gravity is a quite universal force which seems to be present everywhere.

Despite the successes of the inverse-square law of gravity in explaining dynamics of objects on the Earth and celestial bodies, like planets of the solar system, it was challenged, to be more precise, improved and corrected, about two centuries later by Einstein's theory of General Relativity (GR). Einstein's relativity states that time and space are very closely related concepts and it is hence more fruitful to treat them on the same footing, and use the notion of *space-time* rather than time and space individually. According to the Einstein GR a force as universal as gravity should be linked with something as fundamental and universal, that is the space-time itself. In Einstein GR, gravity is tied with a property of space-time called *metric* which is a measure of the distances in space-time and strength of gravity is measured by another property of space-time called *curvature*; the bigger the curvature, the stronger gravitational pull one would feel. Here curvature has essentially the same meaning as one intuitively understands about curvature in surfaces we deal with in daily life. However, instead of two dimensional surfaces, here we have four dimensional space-time.

Einstein GR was introduced in 1915 and like all the other physical theories or models it is described by an equation. Einstein's equation takes the matter and energy distribution as an input and its solutions determine the space-time which is caused as a result of the gravitational pull of the matter and energy inside it. This equation is generically, mathematically hard to solve. Nonetheless, from the early days these equations were introduced, physicists and mathematicians alike, have been working hard to find solutions to these equations. Among the first solutions were the one introduced in 1915, the same year Einstein presented his GR, by German physicist Karl Schwarzchild, and the one given by Russian mathematician and physicist Alexander Alexandrovich Friedmann in 1922. Interestingly both of them fought in the World War I, one in the German side and the other on Russian side, but apparently not on the same front.

The corrections introduced by Einstein GR to the Newtonian gravity are generically tiny in scales we deal with in our daily life, while they are more pronounced in larger scales, or extreme conditions of very high matter density or temperature, or very-very-very short distances which we have not been able to probe up to date. So, GR may be put to test in some different fronts and distance scales, cosmic scales (distance as large as cluster of galaxy size or bigger) where Friedmann solution is expected to be at work; astrophysical scales, the Solar system physics and eventually very-very short distances e.g. probed by particle physics accelerators like LHC at CERN, Geneva.

In fact the first success of Einstein GR was made through an analysis by Einstein himself, considering the corrections GR provides to Newtonian gravity, it was shown that GR, and in particular the Schwarzchild solution, is capable of explaining the mismatch of observations accumulated for a couple of centuries to early 1910's about the orbit of Mercury with the predictions of Newtonian gravity. However, the first experiment designed to test GR came in 1919 and was based on Schwarzchild's solution and the so-called *light-bending* or more technically as it is known today *gravitational lensing*, the fact that within GR setup light will bend while passing around a massive object, like the Sun. Later on some other solutions of GR (other than Schwarzchild) passed observational tests, and to date GR has appeared very successful in confronting with observational data.

Black holes and Horizons

The Schwarzchild solution although very successful in explaining the data as early as 1920's, had some peculiar features and theoretical issues, which in particular made Einstein very unsatisfied and unhappy: the solution had a *singularity* in some specific locus of space-time. Fortunately, in the Schwarzchild case and presumably in all physically relevant cases, this singular region is dressed and is not *naked*; it is hidden behind a *horizon.* Horizon is a locus which only allows for a one way communication with the other side. That is, one can only send or receive signals (but not both) from the other side of horizon and a person outside the horizon has no way to receive information from inside the horizon where the singularity is also located. In other words, singularity is inaccessible to anybody outside. This may make presence of a singularity more tolerable.

Exactly the presence of horizon and that there is a region in space-time that signals can only fall into and cannot come out, prompted American physicist John Wheeler to coin the name *black hole* in 1967 for this kind of space-times. Hence Schwarzchild solution was indeed the simplest black hole predicted by the GR theory. Black holes, as predicted by the theory, are indeed very odd objects: if one approaches the horizon one may simply pass through without feeling anything special, however, once one passed it, there is no escape and no return!. Gravity effects are so strong that it will take infinite time, no matter how hard you try, to go back across the horizon after you crossed it once. Moreover, according to the theory, once one passed the horizon the destined fate is falling into the singularity. Close to the singularity gravity effects and tidal forces are so strong that one would be thorn apart, not of course a pleasant fate. So, the key question is whether black holes can actually form from ordinary matter we find in the world? Another key question is whether such a solution of the GR theory can actually exist in real world? These two questions have both theoretical and observational aspects, to which we turn next.

Can black holes really form?

To see if one can get a gravitational pull so strong as in the black hole case, recall that source of gravity is the mass and as we increase the mass the gravity pull increases. On the other hand, just using naïve intuition coming from the Newton's inverse-square law, one would expect that to get a stronger gravitational pull one needs to extremely squeeze in the matter to become so dense that the whole mass can be compressed behind its horizon. The question is whether in reality such a squeezing can take place. One may make a thought-experiment. Let us consider a lump of gas at very very low temperatures and leave it for a long time. This is in fact very close to the situation which almost all the stars we see today have started from. Under gravitational pull, the molecules of the gas start condensing and squeezing in. If there is no other force acting on these molecules, there is in principle nothing to forbid or stop the squeezing process and the system undergoes the *gravitational collapse* and a black hole forms.

In reality, however, there are other forces. These forces set in when the matter is squeezed to the extent that individual atoms begin to get pushed and squeezed into one another. So, the internal structure of atoms and in fact even the atomic nuclei, also become important. This makes the nuclear forces be important much before the black hole can form. In fact, this is the simplest model for the star evolution: when a lump of gas squeezes in under its own gravity it reaches densities where nuclear processes can start and it becomes a star like our own Sun. This leads to repulsive forces which are generically strong enough to withstand gravitational collapse. The evolution path a star follows, however, is very much depending on its mass and one should hence modify or improve the above simple minded picture. There is a ``critical mass'' above which these other forces, which are of genuine quantum nature, cannot withstand the collapse. This critical mass is about three times the mass of our own Sun. If we start with such a heavy star, at last stages of its evolution it undergoes the dramatic supernova explosion and what remains after the explosion is a black hole. After the black hole formed it starts pulling in any other matter, including other stars or planets and ``eating them up'', becoming even bigger and more massive, the older a black hole, the more massive it is expected to be.

Can we see black holes?

The above is a description of a simplified black hole formation model based on what our current physics theories offer. However, there could be some yet unknown physics involved in the course of a black hole formation in reality. Therefore, our model has a prediction, existence of black holes, which in principle may be tested in astrophysical observations. On the other hand, we can ``see'' things only when a light (or some other signal or messenger) can come out of it and reaches us. But, we just argued that no emission comes out of black holes, so how can we test this prediction?

The answer can come from the ``eating up'' process: *Before* falling into the black hole and passing the no-return point matter leaves behind a trace; it is generically speeded up so much that starts radiating off X-ray or more energetic γ-rays with very specific characteristics, and this radiation may be observed. The X-ray photo of a real black hole is hence expected to be very bright and not black at all. In reality the process which leads to such emissions are very involved and the matter which is eventually going to fall into a black hole is whirling around the black hole while decreasing its orbit radius and, speeding up and radiating. This whirling matter is technically called an *accretion disk*. Another proposal to detect black holes is through the light-bending and gravitational lensing the black hole may cause when the light from other sources pass invicinity of a black hole.

In recent years X-ray astronomy has flourished and many such accretion disks have been observed. Of course there is still debates on whether what has caused this, is a genuine real black hole or other very dense objects like neutron stars (which is another type of supernova remnant). However, there are mounting evidence that we indeed have black holes, very massive black holes, in every galaxy, including our own Milky way. The emerging picture is that at the center of galaxy we indeed have a (super)massive black hole and the whole galaxy is rotating around this black hole whose mass can be as large as the mass of the rest of the objects in the same galaxy. There could of course be black holes in other parts of galaxies away from the center.

Despite the progress, both on observational grounds and at the theory front, physics of black holes still hold a lot of mysteries and many physicists are working hard to open up this black box and uncover its mysteries. One of these mysteries on the theoretical side arose from seminal works of Stephen Hawking since the early 1970's, indicating that black holes are not completely black and actually radiate (known as Hawking radiation), once we combine Einstein's GR with laws of quantum physics. This brings many more questions and mysteries about black holes which are actively under study by theoretical high energy physicists. We hope these studies bears fruit and have a more coherent and clear picture of black holes sometime soon.