

Physics 161: Black Holes: Lecture 23: 1 Mar 2010

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23 Inside the Kerr black hole

Recall that the singularity at $\Sigma = 0$ was a ring of radius a in the equatorial plane. In order to properly investigate the properties inside the Kerr black hole we need some coordinates analogous to the Kruskal-Szekeres coordinates for the Schwarzschild metric. These were found by Kerr and Schild in 1965. They proved that singularity is a ring as described above and also showed that there were other regions inside just like in the Schwarzschild case.

They found that the ring singularity has some very weird properties. As one passes through it one goes through $r = 0$ to negative values of r ! And since r becomes timelike near the ring, for small values of r and θ near $\pi/2$, they found orbits in the ϕ direction that were timelike. Since ϕ a periodic function, this means looping around in ϕ near the ring means looping around in time; time becomes periodic inside the ring! That means that closed time-like loops must exist near the singularity. This is thus a time machine!

Even weirder would be the case the case discussed above where $Q^2/G + a^2 > G^2 M^2$, and there would be no solution for a horizon. This would of course violate the cosmic censorship “no naked singularity” conjecture, but this is only a conjecture at this point. So in the pure Kerr solution, there would be no horizon, but there might still be a singularity! In this case, this would seem to be a “naked singularity”; that is a singularity not protected by a horizon. Because of the closed timelike loops, one can in principle make use of the causality violation occurring near the ring singularity to go “backwards in time” by an arbitrary amount as measured by t coordinate. However, people think that in real stars this can’t happen for reasons we will discuss below.

The full geometry of the Kerr black hole is more complicated and rich than the Schwarzschild geometry, so we want to simplify the drawing of the Kruskal-Szekeres coordinates, by using what are called **Penrose diagrams**. Here we stretch time and space some and draw infinity as an edge. Lightcones stay the same, but the edges represent going all the out to infinity in time or space.

Fig: Penrose diagram of Schwarzschild Black hole

Recall region I is where we start and region II is inside the black hole; once here you have to hit the squiggly line which represents the singularity. Region III is the white hole, and region IV is another asymptotically flat region of space time, which you can’t get to without traveling faster than c .

Fig: Penrose diagram of Kerr Black hole

The Penrose diagram of the Kerr geometry starts out the same as the Schwarzschild diagram, but the inner horizon and the ring singularity makes a difference. The inside of the inner horizon ($r < r_-$) is split into two regions V and VI. Once you pass through the inner horizon you have have a choice. You can either hit the singularity and die, or go through the ring and come out into other regions labeled V’

and VI'. Regions V and VI are still inside the black hole, but regions V' or VI' are other asymptotically flat spacetimes, similar to region IV. In these new asymptotically flat regions, the ring singularity is completely "naked" and has negative mass. With respect to the original region II, the singularity of course is inside the black hole, but for someone in region V' or VI' there is no black hole and it is possible to escape to any distance. At this point one can actually go through the ring again and get a region VII identical in structure to region III, and continue the process ad infinitum! In theory one can extend the structure downward as well through what used to be the white hole.

Note that in the Schwarzschild case one could not travel from region I to region III because the future lightcones all contained the singularity. In the Kerr metric however, this is not true! By going through the ring singularity one can reach another asymptotically flat spacetime without hitting any singularity. So is this a real wormhole? Can a rotating black hole be used as both a wormhole and a time machine? The answer is not yet proved one way or the other! The conjecture is that all the inner structure we have been discussing is unstable. An actual collapse of the spinning star is not perfectly symmetric or smooth. The "no hair" theorems say that one gets to the pure Kerr geometry only after the spacetime settles down. In particular, it is conjectured that the ring singularity is unstable and it is the inner horizon at $r = r_-$ that becomes the actual singularity. In this case, anything going into a Kerr black hole would have to be destroyed. There are several reasons for this and Wald's book has a long description on page 318. One reason is that any small perturbations (light rays or particles) entering the black hole would get an infinite redshift by the time they get to the inner horizon. These would then have to be put into the stress-energy tensor and would destroy the perfect symmetry needed to maintain the ring singularity. The same thing would be true of anyone trying to go through the singularity into another spacetime. Their mass would change the metric so much as to destroy it.