An Explanation for the Mass Gap between Neutron Stars and Black Holes, and a Proposed Unification

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ABSTRACT

Neutron stars and black holes are surprisingly similar objects. I examine the theory behind the maximal mass of neutron stars, and find the assumption that additional gravitational collapse of neutron stars creates black holes to be unjustified. Instead, I propose that black holes are created whenever the radius of a compact object is smaller than the object's Schwarzschild radius. My calculations indicate that this should happen for compact objects of mass larger than about 5.3 $M_\odot$. I propose that the apparent lack of compact objects between slightly larger than 2 $M_\odot$ and about 5 $M_\odot$ occurs because any such objects would be unstable neutron stars that would therefore shed mass.

Keywords: Mass Gap, Neutron Stars, Black Holes, Maximal Mass of Neutron Stars, Gravitational Waves, Unification of Neutron Stars and Black Holes.

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1. Introduction

Neutron stars and black holes are presently considered to be distinct objects. Neutron stars, composed primarily of densely packed neutrons, are often observable as pulsars, and thus emit radiation. Black holes, on the other hand, are believed to emit no significant radiation from the hole itself, because the hole's gravity curves space to such an extent that no light can escape. (Carroll & Ostlie 2007, p. 633) There are caveats to this statement for black holes such as Hawking radiation and the Penrose process, as well as the Blandford-Znajek process, but the rule is believed to hold true but for those exceptions. Another major difference is that black holes are said to be completely described by just three properties: mass, charge, and rate of rotation. (Carroll & Ostlie 2007, p. 640) However, despite these apparent differences, there are surprising similarities between neutron stars and black holes. Each is believed to result from the gravitational collapse of giant stars. And perhaps most striking: many neutron stars and black holes have highly collimated jets of plasma, often moving relativistically, that originate at or very near the poles of the compact object.

In this paper I propose a unification of neutron stars and black holes. I suggest that real world black holes, as opposed to theoretical constructs, are actually neutron stars whose radii are smaller than their Schwarzschild radii. In other words, I suggest a neutron star does not undergo further gravitational collapse to become a black hole. Instead, a neutron star of a certain size becomes a black hole by simple virtue of its radius being smaller than the Schwarzschild radius for an object of its particular mass. See (Carroll & Ostlie 2007, p. 635). I will show that this will happen at about 5 $M_{\odot}$. Of course, to make this argument, I will have to reexamine the prevailing theory of maximal neutron star mass. I will show where that theory is based on faulty premises. I will also examine the curious lack of either neutron stars or black holes between masses slightly larger than 2 $M_{\odot}$ up to 5 $M_{\odot}$. To my knowledge, one of the smallest black holes reported so far with a well determined mass is A0620-00 with a mass of 6.6 $M_{\odot}$. (Cantrell, A.G.; Bailyn, C.D. 2010 at p.29) A 3.8 $M_{\odot}$ black hole was reported, J1650-500, (Thompson, A. 2008) but later retracted with a corrected mass of 5-10 $M_{\odot}$. (Shaposhnikov, N; Titarchuk, L 2009) Additionally, several compact object candidates have been identified for which their mass estimates range across the zone between neutron stars and black holes, but which have error bars that include masses over 5 $M_{\odot}$, or may in fact be neutron stars. See for example, 2MASS J05215658 + 4359220 (Thompson, T. et al. 2019) , Cygnus X-3 (Koljonen, K; MacCarone, T.J., 2017), and GRO J0422 + 32 (Gelino, D.M.; Harrison, T.E. 2003).

Observations of gravitational waves have presented a few candidates for objects in the Mass Gap range. During the third observing run of LIGO, VIRGO and KAGRA, gravitational waves GW190814 and GW200210.092254 each had secondaries close in mass to 2.6 $M_{\odot}$, which would appear to be in the Mass Gap. (Abbott, R, et al. 2020; Abbott, R, et al. 2021) However, Gayathri et al (2023) points out that the mass of these secondaries is about what you would expect for either a binary neutron star system, or a recently merged neutron star binary. In the first case, a binary neutron star system would not be a violation of the mass gap, and in the second case, the merged binary neutron stars may have formed an overweight neutron star, which may have merged with the much larger black hole before having a chance to shed mass due to instabilities.

A gravitational signal, GW230529_181500, was observed in May, 2023, by the LIGO Livingston observatory early in the fourth observing run. (LIGO, 2024). The primary had a mass of 2.5-4.5 $M_{\odot}$, which might be in the mass gap. Even so, it may be an overweight neutron star, which may not have had time to shed mass due to instabilities, before merging with the secondary.

Additionally, there may be unrecognized systematic errors in the masses derived from gravitational wave observations. Only where there are multimessenger observations can we use independent means to verify the masses. So far, that is the case only for the binary neutron star merger, GW170817. Thus, we are unable to use other means to confirm the gravitational wave mass determinations of black holes. An example of a possible systematic error would be the failure to consider the effects of relativistic beaming of gravity during the merger, if that theory should prove correct. (Blake, B.C., 2022; Blake, B.C., 2023). This should become clear in my planned forthcoming paper on Solving the Final Parsec Problem with Relativistic Beaming of Gravity.

2. A Very Short History of the Theory of Maximal Mass of Neutron Stars

Although Walter Baade and Fritz Zwicky first predicted the possibility of neutron stars in 1934 (Baade & Zwicky 1934), neutron stars were not actually discovered until 1967. Jocelyn Bell, working for Antony Hewish, observed repeating radio signals that originated from pulsars, which were neutron stars. (Hewish et al. 1968) However, long before neutron stars were actually discovered, Robert Oppenheimer and George Volkoff published a theory of maximal masses of neutron stars in 1939. (Oppenheimer et al. 1939) Their theory closely followed a similar analysis of white dwarfs by S. Chandrasekhar.

Chandrasekhar astounded the physics community with a theory that predicted a maximal mass of white dwarfs, (Chandresekhar, S. 1931), that limit now accepted as 1.44 $M_{\odot}$. He modelled white dwarfs as a degenerate gas of fermions, and included in his analysis the relativistic speed limit for the electrons in the fermion gas. He showed that contrary to expectations, adding additional mass to a white dwarf would cause the radius to contract rather than expand. When the mass exceeded the maximal mass, the additional contraction would lead to an instability which would cause the white dwarf to undergo gravitational collapse.

Oppenheimer and Volkoff applied a similar analysis to neutron stars. They treated the neutrons as a fermi gas, and arrived at a maximal mass for neutron stars of 0.7 $M_{\odot}$. (Oppenheimer et al. 1939) However, of the neutron stars that have had their mass measured, not a single one has a mass under 0.7 $M_\odot$, which was supposed to be the maximum! Most have masses in a narrow range near 1.4 $M_\odot$, while a few range up to slightly over 2 $M_\odot$. The major problem with Oppenheimer and Volkoff's analysis was their assumption that the neutrons are in a fermi gas. Contrary to that assumption, the neutrons are not believed to be in a gaseous state, but are believed to be compacted together! They have continual interactions between the particles, and these nuclear interactions may provide the support against gravity, rather than just the degenerate forces.

However, the consensus still seems to be that neutron stars have a maximal mass, with one recent estimate putting the limit at 2.16 $M_\odot$. (Rezzolla, L. et al. 2018) One might ask why the idea of a maximum mass still persists when the theoretical basis is somewhat troubling? I think the answer is a practical one. It is simply because we have not found any neutron stars with masses between sightly over 2 $M_\odot$ and 5 $M_\odot$. (Farr, W.M. et al. 2011; Özel, F. et al. 2010)

3. Towards the Unification of Neutron Stars and Black Holes

So, why do we not find neutron stars with masses between a little over 2 $M_\odot$ and 5 $M_\odot$, which is about the smallest mass for which we find black holes? If a neutron star were to accrete enough mass from a binary companion to put it over the mass limit, then shouldn't the neutron star collapse to form a black hole? But then we should find black holes with masses less than 5 $M_\odot$, which we don't! The same problem arises for a collapsar that would result in a neutron star that would weigh between 2+ $M_\odot$ and 5 $M_\odot$. The more plausible conclusion is that something else happens to overweight neutron stars besides gravitational collapse. I suggest, for example, that they may shed mass! This might result if the overweight neutron star becomes unstable because the speed of sound approaches the relativistic limit, see (Kalogera, V. 1996), (Srinivasan, G. 2002), or perhaps because its physical radius approaches the Schwarzschild radius, or perhaps for some other cause of instability. But saying an overweight neutron star undergoes gravitational collapse seems contrary to the known facts.

Where would the shedded mass go? Very likely, the extra mass would enter the neutron star's wind nebula. See for example the wind nebulas of the Crab and the Vela pulsars.

We should also reject the assumption that adding mass to a neutron star will cause its radius to contract, which is a vestige of the fermi gas analysis of white dwarfs. Since neutron stars must be supported by nuclear contact forces between the neutrons, rather than just degeneracy pressure, (Srinivasan, G. 2002), a much more reasonable assumption is that adding mass will increase the radius enough to maintain approximately the same density. An analysis based on that assumption is quite enlightening!

The density of the canonical neutron star of mass 1.4 $M_\odot$ and radius 10 km is $\rho = 6.648 \times 10^{17}$ kg m^{-3}. We will assume for this calculation that all neutron stars have approximately this density.

What we will do is develop a formula for the radius of a neutron star, assuming constant density of 6.648×10^{17} kg m^{-3}. We start with the formula for density, $\rho = m/v$, where m is mass and v is volume. (I use Newtonian calculations for convenience; they should be reasonably accurate for neutron stars.) We will also use the formula $v = 4/3\ \pi r^3$ for the volume of the neutron star, where r is the radius. Substituting m/ρ for v in the volume formula, and inserting the value above for the density, we solve for r to obtain:

$$r_{ns} = \sqrt[3]{\frac{m}{2.7847\ \times 10^{18}\ kg\ m^{-3}}} \tag{1}$$

We will also consider the formula for the Schwarzschild radius r_s of a black hole of mass m:

$$r_s = \frac{2Gm}{c^2} \quad (2)$$

Where G is the gravitational constant and c is the speed of light. Note that for a canonical neutron star of mass 1.4 $M_\odot$, the neutron star radius equals 10 km. But the Schwarzschild radius of a black hole of the same mass, m = 1.4 $M_\odot$, would be r_s = 4.14 km. Thus, for a mass of 1.4 $M_\odot$, the neutron star radius is larger than the Schwarzschild radius. Note that both radius equations, Eq. 1 and Eq. 2, increase monotonically with increasing mass, but that the Schwarzschild radius, Eq. 2, increases more rapidly. Thus, we should be able to find out at what mass the two radii are equal, by setting $r_{ns} = r_s$.

Setting Eq. 1 equal to Eq. 2, and solving for m we obtain m = 5.3 $M_\odot$. Thus, if indeed all neutron stars have approximately the same density of

6.648×10^{17}kg m^{-3}, then any neutron star of approximate mass ≥ 5.3 $M_\odot$ should find itself within its Schwarzschild radius, and therefore be inside a black hole! This should happen without the necessity of any further gravitational collapse! Incidentally, this also means we are unlikely to find any black holes smaller than 5.3 $M_\odot$ that result from stellar collapse. Any such objects should be neutron stars, although of course if they are overweight, they may shed mass.

What we have proposed is that real world black holes are just neutron stars within their Schwarzschild radius. Black holes that have grown larger though accretion or mergers, including supermassive black holes, should be seen in the same way. Since the Schwarzschild radius grows much faster by mass than the neutron star radius, there is plenty of room for the compact object inside of even a supermassive black hole. But what about some of the other differences between neutron stars and black holes? Can they be accounted for?

One difference is the characteristic pulsations that come from some neutron stars, that is, pulsars. Why do there not seem to be any pulsating black holes? The answer lies in the mechanism for neutron star pulsation. The pulsar is believed to have a magnetic pole out of alignment with its rotational pole. The pulses are the result of beams of particles that emit from the magnetic pole and sweep across the sky due to the misalignment with the rotational pole. Thus, from earth we see intermittent pulses from the neutron star. But place that pulsar inside of a black hole and it will no longer sweep across the sky because the beam will not be able to penetrate the event horizon, which occurs at the Schwarzschild radius!

Another difference between neutron stars and black holes relates to the spin. Neutron stars have in general much lower spin parameters than black holes. In fact, if neutron stars have a spin parameter larger than 0.7, they are expected to fly apart, because the centrifugal force will be larger than the gravitational binding force. (Branch & Wheeler 2017 at p.599) But black holes regularly have spin parameters larger than 0.7. (Branch & Wheeler 2017 at p. 603) So, why can a neutron star inside its Schwarzschild radius spin must faster without flying apart? It is because within a black hole, all matter is enclosed within trapped surfaces, so it cannot move outwards, towards the Schwarzschild radius. (Penrose, R. 1964) Thus, the neutron star inside the black hole cannot physically fly apart.

4. Conclusion

In this paper we have suggested unification between neutron stars and black holes. We have suggested that neutron stars become black holes if their physical radii are smaller than their Schwarzschild radii, i.e. that no further gravitational collapse is required. Therefore, we are saying that black holes have compact objects inside. We made the reasonable assumption that the density of all neutron stars is approximately the same, and used this to determine that the physical and Schwarzschild radii would be equal at about 5.3 $M_\odot$. This then provides an explanation as to why we do not find black holes resulting from collapsed stars that are smaller than 5 $M_\odot$, because they would be neutron stars. As for the lack of neutron stars between 2.16 $M_\odot$ and 5 $M_\odot$, we presume overweight neutron stars shed mass due to instabilities.

I would like to point out that the figure of 5.3 $M_\odot$ is not especially robust. For example, if one were to use 12 km rather than 10 km for the radius of a canonical 1.4 $M_\odot$ neutron star, and perform a similar calculation, the mass at which the physical and Schwarzschild radii would be equal would be about 7 $M_\odot$. Additionally, the assumption that all neutron stars have the same density may not be strictly true, and any deviation would affect the calculation as well. While the calculation may not be precise, it still suggests that black holes may arise because the neutron star radius is smaller than the Schwarzschild radius, rather than because of further gravitational collapse.

One might wonder why it is important to distinguish between whether real world black holes contain compact objects, or whether they have singularity inside. If we cannot see inside a black hole, how does it matter? For one thing, we understand much about how compact objects such as neutron stars behave, which makes it possible to perform calculations. For me, this will be very important in my next paper when I investigate whether the jets from neutron stars and black holes have a common origin.

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