**Is a black hole a neutron star?**

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## Abstract

The existence of black holes in the universe has been confirmed by observations. However, the theoretical model is still disputed. Einstein rejected their existence, although their theoretical existence is based on GR because Schwarzschild's solution predicted a singularity point at their center. He claimed that this is not a physical solution. On the other hand, Penrose suggested that their theoretical singularities exist. Kerr, who solved GR equations of a rotating black hole claims that Penrose did not prove the exitance of the singularity point at the center of a black hole.

The thesis of the paper is: A black hole is a compact neutron-star-like objects hidden inside an event horizon rather than singularities. On the other hand, a neutron star is a compact object that its physical radius is bigger than the event horizon and therefore can be seen.

Based on this hypothesis, we investigate whether the model can account for the historically observed scarcity of compact objects between the most massive neutron stars and the lowest-mass stellar black holes, commonly referred to as the compact-object mass gap.

## Current status

Blackholes' existence in the visible Universe was predicted by solving GR equations. In 1916 Karl Schwarzschild obtained the first exact spherically symmetric vacuum solution of Einstein's field equations. In its modern interpretation, the maximally extended Schwarzschild geometry contains an event horizon at r=2GM/c2 and a curvature singularity at r=0. This singularity implies that the known laws of physics break down. Einstein rejected this singularity. In a paper from 1939, Einstein concluded that there was no way a Schwarzschild singularity could ever be possible and therefore the Schwarzschild singularity does not exist in physical reality. The second radius is known as the Schwarzschild radius or the event horizon. The event horizon is a radius that is non-physical but nothing within it, including light, can escape the gravity of the black hole. Thus, an observer located outside the event horizon cannot see what is behind it.

Schwarzschild radius is given by: $R_h = \frac{2 \cdot G \cdot M}{C^2}$

Where: G- gravitational constant, M- Mass of a black hole, and c- speed of light.

Nevertheless, despite Einstein's and other physicists' objections to the existence of black holes, black holes have now been observed through gravitational-wave detections and horizon-scale imaging, e.g., M87* that was taken in 2019.

A historical note: The idea of the possible exitance of black holes was first suggested, in 1783, by John Michell. Based on Newton's escape velocity equation he calculated what is the mass of a star that will not enable anything, even light, to escape from the star. He found the same equation of Schwarzschild radius.

In December 2023, Roy Kerr, the discoverer of the Kerr solution describing the spacetime surrounding a rotating black hole, published a paper entitled *Do Black Holes Have Singularities?* [1]. In this work, Kerr reexamines the long-standing interpretation of black-hole singularities and argues that there is no proof that black holes formed by the gravitational collapse of real physical bodies must contain spacetime singularities. He challenges the common interpretation of the Penrose–Hawking singularity theorems, arguing that while these theorems establish the existence of incomplete geodesics under certain conditions, they do not by themselves demonstrate the formation of a physical singularity at the center of a collapsing star. Kerr further notes that the ring singularity appearing in the mathematical Kerr solution should not necessarily be interpreted as a physical object. In his words, "the ring singularity is just a replacement for a rotating star." He suggests that a physically realistic rotating matter distribution could replace the mathematical singularity while preserving the exterior Kerr geometry.

The present work adopts this viewpoint as a physical hypothesis. Specifically, it is proposed that the interior of a black hole contains a finite-density, rotating neutron-star-like core rather than an infinitely dense singularity. The event horizon remains a genuine prediction of General Relativity, but the central singularity is replaced by a compact object composed of matter at approximately nuclear density. This interpretation is consistent with Kerr's suggestion that the interior of a realistic rotating black hole may be represented by a physical rotating body rather than by a mathematical singularity.

**Is there an infinite density at the center of a black hole.**

We propose that physical collapse terminates before the mathematical singularity predicted by classical GR is reached. We adopt as a working hypothesis that stable baryonic matter cannot exceed nuclear density, i.e., ~7.8*10^17 kg/m^3. This maximum density is found also in the nucleus of an atom and in a neutron star. The density of a neutron star is 3.7x10^17 to 5.9x10^17 kg/m^3, which is comparable to the approximate density of an atomic nucleus of 3x10^17 kg/m^3. [2].

<u>Note:</u> There are additional hypotheses regarding the maximal density in the Universe. The first is a quark star that has a density of 10^19kg/m^3. Strange Quark matter is actively studied with particle colliders, but this can only be produced at very hot temperatures (above 10^12 K) and in

blobs the size of atomic nuclei, which decay immediately after formation. No stars made of strange quark matter were observed in the Universe. The second is a Preon star that has a density of 10^26kg/m^3. No evidence for quark and Preon stars has been found. see [3]

The density inside a neutron star is **not uniform**. Modern neutron-star models, obtained by solving the Tolman–Oppenheimer–Volkoff (TOV) equations with realistic equations of state, predict that the density increases continuously from the surface toward the center. In the present model, we adopt as a working hypothesis that gravitational collapse of baryonic matter does not produce arbitrarily large densities. Specifically, we assume a limiting density $\rho_{max}$ =7.8×10^17 kg/m^3. This value is adopted phenomenologically as a characteristic nuclear-density scale. It is not a consequence of General Relativity or of the presently established neutron-star equation of state. The consequences of this assumption for compact-object radii and black-hole formation are examined below.

There are QCD measurements that demonstrate the existence of enormous repulsive QCD stresses within nucleons, suggesting that nuclear matter may possess a finite maximum compressibility.

1) Experiments that measure the force between two nucleons as a function of the distance between them show that the force between them can be described by the graph shown in [4]. This graph is based on Reid's potential formula. It shows that for a distance smaller than 0.8fm, the force becomes a sizeable repulsive force. Further analyzing Reid's equation shows that at r → 0 the potential as well the force between nucleons becomes strongly repulsive.
2) Physicists at Jefferson Lab did another experiment "QUARKS FEEL THE PRESSURE IN THE PROTON" [5]. They measured the distribution of pressure inside the proton. The findings show that the proton's building blocks, the quarks, are subjected to a pressure of 100 decillions Pascal (10^35) near the center of a proton, which is about ten times greater than the pressure in the heart of a neutron star. The meaning is that the outward-directed pressure from the center of the proton is higher than the inward-directed pressure near the proton's periphery and therefore a neutron star cannot collapse.

**Why is a neutron star visible whereas a black hole is not?**

Given the description above, the question now is how come black holes are not directly observed in the Universe, while neutron stars are seen. We claim: **The visibility depends on the relation between the physical radius of the neutron star and its Schwarzschild radius $R_h$**. A celestial body will be observed if its physical radius is bigger than its Schwarzschild radius. On the other hand, a celestial body that has a physical radius that is smaller than its Schwarzschild radius will be hidden.

The minimum mass and radius of a blackhole can be found in the following manner:

1. Given a celestial body with mass $M$.

2. The radius of a densely packed spherical celestial body is:

$$R_n = R_{neutron} \cdot \left(\frac{M}{m_{neutron}}\right)^{1/3} \qquad (1)$$

See: https://en.wikipedia.org/wiki/Atomic_nucleus

where:

Mass of Neutron: $m_{neutron} = 1.6749275 \cdot 10^{-27}\, kg$

Radius of Neutron: $\mathrm{R}_{neutron} = 0.8 \cdot 10^{-13}\, cm$

3. The Schwarzschild (or event horizon) radius of a celestial body is:

$$R_h = \frac{2 \cdot G \cdot M}{c^2} \qquad (2)$$

where:

Gravitational constant: $G = 6.67 \cdot 10^{-11} \frac{m^3}{kg \cdot \sec^2}$

Light velocity: $\mathrm{c} = 2.99 \cdot 10^8 \frac{m}{\sec}$

4. Equating Schwarzschild radius of the celestial body to its physical radius; $(\mathrm{R}_H = R_n)$ :

Gives: $$M_{\text{limiting}} = \left(\frac{R_{neutron} \cdot c^2}{2 \cdot G \cdot m_{neutron}^{1/3}}\right)^{3/2} = 9.67 \cdot 10^{30}\, kg \sim 4.86 Sun - masses. \qquad (3)$$

and $R_{\text{limiting}} = 14.35 km$

From the above calculations (1) to (3), it is shown that the limit between a neutron star and a Blackhole is 4.86 Sun masses and a radius of 14.35km. A celestial body with a mass higher than 4.86 Sun masses will become a Blackhole because its physical radius is smaller than its Schwarzschild radius.

**Observations**: The calculated minimal mass of a black hole in the Universe is in good agreement with observations. A summary of observations of black holes and neutron stars is shown in the graph: [6].

**Kerr solution for a rotating black hole**

The preceding calculations assumes a nonrotating, spherically symmetric neutron star. The derivation of the above equations (1), (2) and (3) is based on Newton's escape velocity and the Schwarzschild solution to GR. Nowadays, it is known that all celestial bodies in the universe spin, albeit at different speeds of rotation. A black hole or a neutron star that is formed by the gravitational collapse of a massive star must retain the angular momentum of this progenitor star. In SBH (Schwarzschild black hole), it is assumed that the mass collapses to an infinitely small point. However, as a point cannot have angular momentum, the conclusion is that SBH is merely a mathematical solution of GR. In 1963, Kerr suggested a solution of GR equations- Kerr black hole (KBH) that takes into consideration the spinning of celestial bodies. Analyzing Kerr's solution shows that KBH has a singularity ring located around its center with radius $R_{s,}$ rather than the point singularity as in SBH. We postulate an additional condition: the nucleus (i.e., the neutron star) of the black hole must reside inside the ring singularity.

The ring singularity radius ($R_s$) can be calculated by using Kerr solution:

$$a = \frac{J}{M \cdot c}$$ ....Black hole spin parameter (or angular momentum per unit mass) (5)

$$R_g = \frac{G \cdot M}{c^2}$$ ...Black's hole gravitational radius

$$a' = \frac{a}{R_g} = \frac{a \cdot c^2}{G \cdot M}$$ .... Dimensionless spin parameter. Ranging from 0 to 1. (6)

Note: Sometimes it is possible to find a' of a black hole by meaurement. Then a' is used in (7) and (8)

$$R_s = \frac{a' \cdot G \cdot M}{c^2}$$ .....The radius of the ring singularity (7)

$$R_{h+} = \frac{G \cdot M}{c^2}(1 + \sqrt{(1+(a')^2})$$ ...The radius of the outer event horizon (8)

Where:

$J$ ....Angular momentum of rotating black hole.

$M$ ...Mass of a Black hole.

c ...Speed of light

$G$ ...Gravitational constant

The dimensionless spin parameter a' ranges from 0 (non-rotating Schwarzschild black hole) to 1 (extremal Kerr black hole).

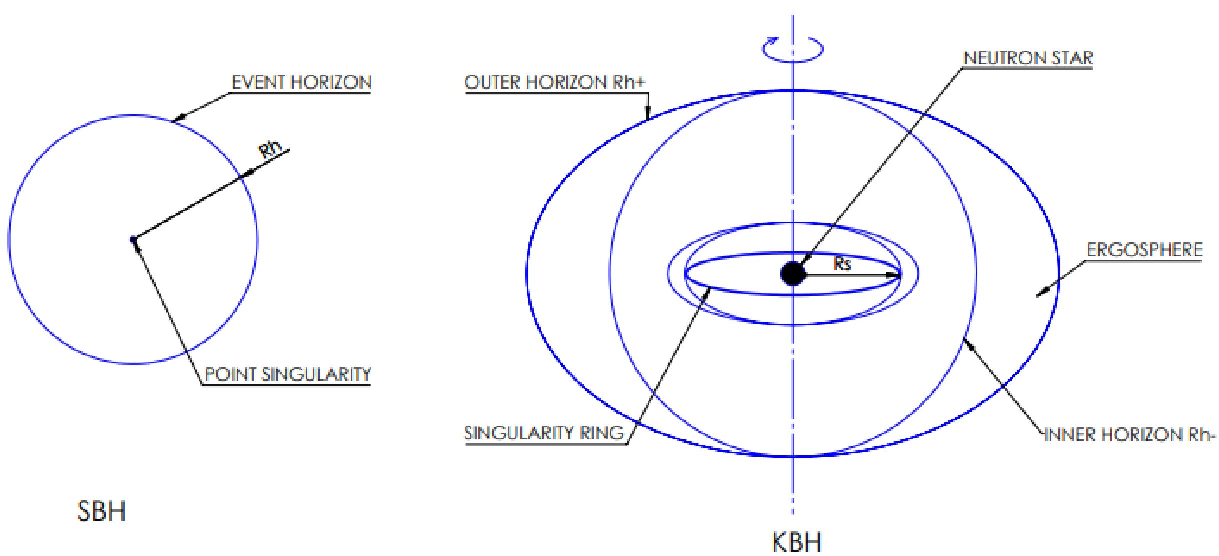
- For a non-rotating black hole, a'=0, the singularity is a point, and the event horizon is calculated by (2)
- If the black hole is rotating, 0 < a' <1, and the singularity becomes a ring.
- In the extremal case, a'=1 with the maximum radius of the ring is Rs=Rh/2

It can be concluded that SBH is a private case of KBH. Moreover, as observation shows in reality, that all celestial bodies spin, there is no non-rotating black hole, and therefore a' > 0. We propose that physical collapse terminates before the mathematical singularity predicted by classical GR is reached.

The ring singularity is confined within the black hole's event horizon and lies in the equatorial plane of the black hole.

To exist the radius of the black hole solid nucleus $R_n$ (1) must be smaller than the radius $R_s$ (7). However, what determines whether the massive celestial body is a black hole or a neutron star is the event horizon $R_{h+}$.

The following figure is a schematic comparison between SBH and KBH.




**Black hole (Cygnus X-1)**

An example of black hole (Cygnus X-1) is given: The solid neutron star radius $R_n$, the singularity ring radius $R_s$, and the outer event horizon radius $R_{h+}$ are calculated. It is shown that for a black hole $R_{h+} > R_s > R_n$.

Given (from observations):

$M = 21.2 \cdot M_{sun}$ ...Cygnus X-1 black hole's mass

$a' = 0.98$ ...Measured dimensionless spin parameter of the Cygnus X-1 black hole.

*Thus*:

$$R_s = \frac{a' \cdot G \cdot M}{c^2} = 30.68 \cdot \text{km} \quad \text{...The radius of the ring singularity} \quad \text{From (7)}$$

$$R_n = R_{neutron} \cdot \left(\frac{M}{m_{neutron}}\right)^{1/3} = 23.45 \cdot \text{km} \quad \text{... Radius of neutron star} \quad \text{From (1)}$$

$$R_{h+} = \frac{G \cdot M}{c^2}(1 + \sqrt{(1+(a')^2}) = 37.54 \cdot \text{km} \quad \text{...Event horizon radius} \quad \text{From (8)}$$

Conclusion: $R_{h+} > R_s > R_n$

Within the model proposed in this paper, the finite-density rotating core is therefore entirely enclosed by both the Kerr ring radius and the event horizon. Consequently, the core cannot be observed directly by an external observer, and Cygnus X-1 is identified as a black hole rather than as a visible neutron star.

The above analysis is based on a measured spin parameter of Cygnus X-1**:** a’=0.98. It is interested to calculate Rn, Rs and Rh+ in the range 0<a’<1.

For the fixed mass of 21.2Msun, Rn=23.45km is constant; only Rs and Rh+ vary with spin.

The Kerr ring scale Rs and the outer Kerr horizon Rh+ are calculated from (7) and (8)

The results are:

| a’ | Rn km | Rs km | Rh+ km |
|---|---|---|---|
| 0.00 | 23.45 | 0.00 | 62.61 |
| 0.10 | 23.45 | 3.13 | 62.45 |
| 0.20 | 23.45 | 6.26 | 61.98 |
| 0.30 | 23.45 | 9.39 | 61.17 |
| 0.40 | 23.45 | 12.52 | 60.00 |
| 0.50 | 23.45 | 15.65 | 58.42 |
| 0.60 | 23.45 | 18.78 | 56.35 |
| 0.70 | 23.45 | 21.91 | 53.66 |
| 0.80 | 23.45 | 25.04 | 50.09 |
| 0.90 | 23.45 | 28.17 | 44.95 |
| 0.95 | 23.45 | 29.74 | 41.08 |
| 0.98 | 23.45 | 30.68 | 37.54 |
| 0.99 | 23.45 | 30.99 | 35.72 |
| 1.00 | 23.45 | 31.31 | 31.31 |

The first important result is that for the entire Kerr spin range Rn<Rh+. Thus, from the horizon criterion of this paper, the neutron star is hidden behind an event horizon for every allowed spin.

The second condition for a black hole is: Rn < Rs < Rh+. Define: $r_g$ =(G*M)/c^2. The Kerr ring scale Rs=a’* $r_g$

The value of a′ at which the core just fits inside the Kerr ring scale is obtained from Rn=Rs=a’*$r_{g.}$

Therefore, $a'_{crit}$ =Rn/ $r_g$ =23.45/31.31=0.749. So, if a’> 0.749 then Rn < Rs < Rh+, and therefore satisfies the proposed geometrical black hole criterion.

**Neutron star PSR J1903+0327**

PSR J1903+0327 provides an example of a rotating neutron star. Taking its mass, its dimensionless spin parameter and adopting the limiting density the physical radius obtained from the uniform-density approximation $\rho_{max}$=7.8×10^17 kg/m^3.

Given (from observations):

$M = 1.667 \cdot M_{sun}$ ...Neutron star's mass

$a' = 0.5$ ...Assumed illustrative spin parameter of the neutron star.

$$Rs = \frac{a' \cdot G \cdot M}{c^2} = 1.24 \cdot \text{km}$$ ...The radius of the ring singularity From (7)

$$Rn = R_{neutron} \cdot \left(\frac{M}{m_{neutron}}\right)^{1/3} = 10 \cdot \text{km}$$ ... Radius of neutron star From (1)

$$Rh+ = \frac{G \cdot M}{c^2}\left(1+\sqrt{1-(a')^2}\right) = 4.23 \cdot \text{km}$$ ...Event horizon radius From (2)

Conclusion R*n* > Rh+ > R*s*

The physical surface of the neutron star therefore lies outside both the formal Kerr horizon radius and the Kerr ring radius. Within the model proposed in this paper, PSR J1903+0327 is consequently visible as a neutron star rather than hidden as a black hole. The Kerr radii quoted here are reference radii calculated from the object's mass and assumed spin; because the stellar surface lies outside them, they do not represent an actual event horizon or physical ring singularity.

## A Possible Explanation for the Compact-Object Mass Gap

Using the formulas above, one can derive a minimum black-hole mass of approximately 4.86M⊙ , but **one cannot derive a maximum neutron-star mass of from those formulas alone**. The neutron-star mass limit must be introduced separately through neutron-star stability physics, such as the Tolman–Oppenheimer–Volkoff (TOV) limit and the equation of state.

A recent analysis found: $M_{TOV}$=2.2-2.3M⊙, and $R_{TOV}$=12 km. [7]. It is to be noted that these numbers are not exact constants, but representative.

To sum up: the Compact-Object Mass Gap is:

**2.2-2.3M⊙ < $M_{GAP}$ < 4.86M⊙**

**Note**: In 2023, the gravitational-wave event GW230529 changed the observational picture of the compact-object mass gap. The binary system consisted of two compact objects. The heavier component was estimated to have a mass of approximately 2.5-4.5 $M_\odot$, while the lighter component was estimated to have a mass of approximately 1.2-2.0$M_\odot$. Current analyses favor the interpretation that the heavier component was a low-mass black hole and the lighter component a neutron star, although the nature of the heavier object was not established unambiguously from the gravitational-wave signal alone.

The importance of GW230529 is that the inferred mass of its heavier component lies within the traditionally proposed compact-object mass gap. However, in applying the model developed in this paper, it is necessary to distinguish from compact objects observed black holes whose near-hole spacetime can be approximated as stationary Kerr, such as Cygnus X-1, and compact objects in the strongly dynamical late-inspiral and merger regime, such as GW230529. For an isolated rotating object, the exterior spacetime can be approximated by the Kerr solution and the characteristic radii Rn and Rh+ can be compared directly. In a close binary system, however, the spacetime is a two-body dynamical geometry influenced by orbital motion and tidal fields. Therefore, applying the isolated Kerr relations directly to the components of GW230529 requires additional treatment of the binary spacetime and cannot, by itself, determine whether the 2.5-4.5$M_\odot$ component is compatible or incompatible with the model proposed here.

**References**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