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Stellar Remnants and Quantum Mechanics: Bridging General Relativity and Quantum Theory

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Introducing Fundamental Concepts of General Relativity

General Relativity is based on the premise of the following equation:

$$G_{\mu\nu} = \left(\frac{8\pi G}{c^4}\right) T_{\mu\nu} \tag{1}$$

that expresses the equivalence between *Einstein's tensor* $(G_{\mu\nu})$ and the *energy-momentum tensor* $(T_{\mu\nu})$. The part within the brackets has no physical meaning – rather it is a constant. Einsteins tensor represents the measure of spacetime curvature. Therefore, the above equation can be expressed as a conceptual equation, according to which:

(spacetime geometry – curvature) = (mass – energy)

In other words, *wherever there is matter or energy, the spacetime is curved.* According to Einstein's General Relativity ***"gravity is the manifestation of the curvature of spacetime"***

This means that gravity is a result of curved spacetime – and therefore a result of the presence of matter or energy.

Compactness and the Intensity of Spacetime Curvature

In order to set a curvature index, we need a relative measure. In other words, the ratio between two quantities. One quantity must show how intense gravity is – and therefore, it is related to the object's mass. The other quantity must show how this mass is distributed in space – and therefore, it's related to its dimensions. Einstein's equations provide an enlightening view on this matter.

$$\begin{pmatrix} Relative\ intensity \\ of\ spacetime\ curvature \end{pmatrix} \sim \left(\frac{G}{c^2}\frac{M}{R}\right) = \frac{object's\ mass}{object's\ size}$$

The term $\frac{M}{R}$ is compactness. M stands for mass and R for radius.

As you can understand, if the object's mass becomes greater, the *curvature intensity (ϵ)* becomes greater as well.

On the other hand, if the object's radius gets smaller, intensity becomes greater once again. Thus:

$$\epsilon \propto \frac{M}{R}$$

The full understanding of stellar remnants requires a full understanding of their *formation process*, in advance. For this reason, we must begin this journey to grasping the greatest "wonders" of nature, starting from ***stellar nebulae.***

From Nebulae to Protostars

A nebula is a region in space, where significantly large amounts of gases, such as *hydrogen* and *helium*, as well as *dust* and *other elements* are concentrated. Nebulae can be disturbed by multiple factors – most often ***Supernova*** explosions.

Such a disturbance causes instabilities in the nebula, since it affects the distribution of mass in it. In other words, in some parts, more matter will accumulate – therefore the gravitational field will be stronger in these parts.

So, if a part of the nebula collapses under its own gravity, it will concentrate more mass from its surroundings and compress it. The more matter is concentrated, the stronger the gravitational field will become.

In this way, the large concentrations of mass create a very dense object – a *protostar.* As the protostar becomes denser, its temperature increases as well.

From Protostars to Stars

When the protostar's temperature reaches *10 million °C* the thermonuclear fusion of hydrogen into helium is triggered. Specifically, under such circumstances, atoms are compressed together, until their nuclei combine. This happens, because atoms vibrate intensely in high temperatures – so, the repulsive force between the positively charged atoms reacting with each other is overcomed.

In the beginning of a star's "life", it combines 4 hydrogen atoms to create a helium-4 atom. The mass of the helium- atom is slightly smaller than the aggregation of the four hydrogen atoms. This small mass deficit is released in the form of energy, as predicted by the equation

$$E = mc^2.$$

A star that undergoes stable fusion is called a *main sequence* star. Our *Sun* is also considered in this category.

Hydrostatic Equilibrium

As a result of fusion, a balance is maintained between the star's gravity and internal pressure. In other words, while the star's own gravity tends to crush it, the pressure and heat from the core prevent this.

White Dwarfs

However, at some point the hydrogen runs out – the core's composition is mostly helium that cannot be fussed into heavier elements, given that the star's temperature is insufficient. So, the star will start to shrink, under its own gravity. In this way, the pressure from the core – and thus the star's temperature – increases. Consequently, the thermonuclear fusion of helium is triggered, and star expands again.

At some point, helium runs out too. A star less massive than **8 – 10** ***MΘ*** start to shrink. During this process the star exhibits an instability between its outer layers and the stellar core. In this way, the outer layers explode.

As a result, the outer layers create a planetary nebula, at the center of which there is the extremely dense remnant of the star – a ***white dwarf.***

Electron Degeneracy Pressure

Inside white dwarfs, thermonuclear fusion does not occur. The balancing of the force of gravity is due to a *quantum phenomenon*. This phenomenon is the *degenerate motions of electrons*, or ***electron degeneracy.***

Electron degeneracy is a result of *Pauli's Exclusion principle*. This principle of quantum mechanics states that two fermions in the same system cannot have the same quantum state. That is to say that they cannot have the same values in quantum numbers, such as: energy level *(n),* orbital type *(ℓ),* orbital orientation (m_ℓ) and spin up or spin down (m_s).

It is a well-known fact in quantum mechanics, *that electrons tend to occupy the energy levels with the least possible energy* – also known as the *ground state.* As the star's nucleus shrinks to become a white dwarf, its volume decreases. Therefore, the available quantum states become less, given that:

$$N \propto V,$$

where N stands for the number of the available quantum states.

As a result, electrons occupy higher energy levels. Higher energy implies greater momentum – thus, higher kinetic energy in electrons.

As regards to stars with a mass greater than ***10 MΘ***, the following must be noted:

Stars of this mass reach multiple stages of fusion. At some point, they reach the stage of thermonuclear fusion of Iron (^{56}Fe). However, this is an *endothermic reaction.* This means that the heat needed to make the reaction happen is more than it gives off.

So, the star loses heat – thus, it cannot balance its gravity. Consequently, gravity becomes dominant. The star collapses under its own gravity. Thus, matter is compressed, and electrons combine with protons, creating neutrons, while at the same time releasing *neutrinos*.

At some point, matter cannot be compressed any further, because of *Neutron Degeneracy Pressure*. That is to say, that neutrons – as fermions – exhibit a degenerate form of motion, prescribed by Pauli's Exclusion Principle, as previously noted.

The outer layers of the star collapse onto the extremely dense core, rebounding and being expelled at tremendous velocities in a ***supernova*** explosion. The neutrinos that were mentioned previously make the propagation of the explosion's shock wave even greater.

Then, there are two possible endings for the neutron nucleus, that are determined by its mass.

If the core is less massive than **2 – 3 *MΘ***, then it will remain a *neutron star*, as predicted by the ***Tolman–Oppenheimer–Volkoff (TOV) limit.***[1] This star balances the force of its gravity with the degeneracy pressure of neutrons in its interior.

However, if the neutron core is more massive than the *TOV limit*, the neutron degeneracy pressure will be insufficient to balance the force of gravity, so there would be nothing to prevent the gravitational collapse.

At this point, let's recall what was mentioned in the beginning about compactness.

According to Buchdahl's theorem, if the radius of an object is less than about 12.5% larger than *the radius of a black hole (R_s)* with the same mass, the object will inevitably collapse into a black hole.

$$R \geq \frac{9}{8}R_s = 1.125R_s = 12{,}5\%\ R_s$$

So, if the neutron core shrinks beyond this limit, it will form a black hole.

Black holes

Black holes are regions of spacetime, where gravity is extremely strong. Black holes form an event horizon – a mathematical surface that defines the boundary where the velocity needed to escape exceeds the speed of light. Since nothing can travel faster than light, nothing can escape.

General Relativity predicts that at the center of black holes, there is a *spacetime singularity* – an anomaly. A singularity is a point where every natural quantity becomes infinitely great. Density, for instance, becomes infinite.[2]

Also, it's a point in spacetime, where the equations of general relativity cannot be solved – this implies that the laws of nature break down. Apart from the singularity, it is believed that black holes are empty space.[3]

However, the fact that the mass of a star is concentrated in a point in spacetime seems rather unpleasant to think of. Hence, General Relativity is indeed unfinished, despite it being correct.

The Holy Grail of the 21st Century

One of the greatest challenges of the 21st century's physics, is unifying General Relativity and Quantum Mechanics and creating a *Theory of Everything.* So far, the two fundamental theories seem to be incompatible.

String Theory

The fundamental idea of string theory is that elementary particles are not points, rather they are one-dimensional oscillating strings.

Hawking Radiation

In 1974, Stephen W. Hawking, first asserted that black holes are actually not black – they emit thermal radiation. So, as they emit radiation, they lose mass over time, they evaporate, and eventually disappear. Once they completely evaporate, nothing is left behind – no information about what has fallen into the black hole.

This loss of information is called the *Information Paradox.* Quantum mechanics requires that *information is preserved*, but general relativity implies that it can be lost.

Instead of describing the black hole only geometrically (through general relativity), *we can see it as a collection of D-branes and strings*. The different patterns in which the strings can oscillate and the D-branes can interact correspond to the microstates of the black hole.

In the context of string theory, we can directly study the emission of particles from these D-branes. Calculations showed that the spectrum of the emission matches the thermal Hawking radiation predicted by classical theory. So, information is not lost, but instead encrypted in Hawking radiation.

The existence of Hawking radiation, suggests that we should not be looking at this matter from two opposite points of view. We need a theory that unifies them.

Loop Quantum Gravity (LQG)

Loop Quantum Gravity is a potential theory of everything that quantizes spacetime itself. In LQG, spacetime is not continuous, but quantified on the Planck scale.

The theory in question provides an alternative approach to black holes, that avoids the singularity. As the neutron core that was mentioned previously collapses, becoming a black hole, a limit is reached where the quanta of spacetime cannot be compressed any further. This creates a repulsive force, which stops the collapse. As a result, the singularity is replaced by a bounce.

Some models suggest that a black hole can "bounce" and turn into a white hole (the theoretical opposite of a black hole). Once again, this reminds us of how important it is to unify General Relativity and Quantum Mechanics.

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[1] This limit applies to cold and non-rotating neutron stars, as rotation and high temperature contribute to maintaining a balance between gravity and the star, leading to a deviation of about 20% in the upper limit value.

[2] Given the formula of density, we must divide the objects mass – a finite number – with its volume – which is equal to zero, since the singularity is a point. Provided that the volume becomes the smallest possible (zero), density must become the greatest possible (infinite), since the two quantities are inversely proportionate.

[3] This poses a significant question to the scientific community: “How can the laws of nature break down in specific areas in the universe? Do they break down in other areas that we are not aware of?”