

The Stars Beyond the Ordinary: The Outlaws Breaking the Laws of Physics



Most of what we know about the universe is built on the **Standard Model** of particle physics, a set of rules that governs how atoms behave from the core of our Sun to the far reaches of the Hubble Deep Field. The stars we know follow a predictable life cycle: they fuse elements, eventually run out of fuel, and collapse under their own gravity until they either stabilize as a white dwarf, crush into a neutron star, or vanish into a black hole.

But there are theoretical objects that under extreme conditions begin to challenge our understanding of density, stability and the very laws of physics themselves. These objects are not just the usual dense balls of gas; they are places where the very pixels of reality, protons, neutrons, and quarks, are toyed with into forms of matter that should not exist. These are not just science fiction; they are the mathematical consequences of our current laws of physics being pushed to their absolute breaking point.

STRANGE QUARK STARS: THE UNIVERSE'S STABLE SOUP

So first of all, what are **quarks**? In the Standard Model of physics, quarks are the fundamental building blocks of matter. While there are six types, namely: Up, Down, Charm, Strange, Top and Bottom, almost everything we see in the visible universe is made of just two: Up and Down quarks. These are the particles that bundle together in triplets to form the protons and neutrons inside your atoms.

In a typical star, these quarks are locked tightly inside. Even in a neutron star - the densest known object besides a black hole, matter inside it is mostly **hadronic**.

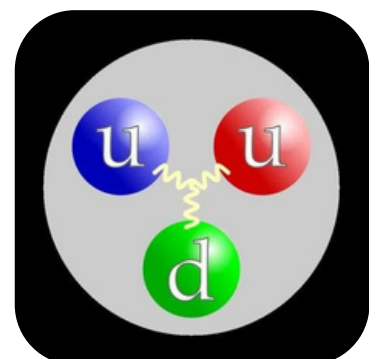


Diagram of quarks in a proton by ResearchGate

Hadronic refers to particles called hadrons which are sub-atomic particles composed of quarks which are held together by a strong nuclear force.

Imagine the protons and neutrons are squeezed together like a giant bag of marbles, but remain individual units. However, if the pressure at the centre of a dying star is high enough, these "marbles" break. The boundaries of the protons and neutrons dissolve, creating **Quark Matter**. This is a state of matter where the quarks and gluons are no longer confined inside hadrons. Instead, they become a deconfined fluid, a subatomic soup in which particles roam freely across the entire core of the star.

In this ultra-dense soup, the energy is so high that some of these down quarks spontaneously transform into strange quarks. This creates **Strange Matter**, a highly theoretical, incredibly dense, and stable mixture of up, down, and strange quarks.

According to the Bodmer-Witten hypothesis, Strange Quark Matter is the absolute ground state of matter. Meaning it is more stable than the atoms in your body. If you could create a lump of Strange Matter in a vacuum, it would sit there forever and ordinary matter could convert into strange matter, and strange stars or strangelets might exist in the universe...

Strangelets are microscopic fragments that could theoretically be ejected during a star's birth or in a collision. If it touches a regular nucleus, it would instantly convert that nucleus into strange matter to reach a lower energy state.

Scientists believe that the supernova remnant **HESS J1731-347** matches the signature of a strange, liquid quark core, and they are trying to find these strangelets in its cosmic rays.

AXION STARS OR THE INVISIBLE GHOST CLOUDS?

To understand the axion star, we have to look at a particle that has never been officially seen, but it might outweigh all the stars and galaxies combined. Axions are hypothetical subatomic particles that are billions of times lighter than an electron and carry no electric charge. They were initially proposed to solve the **strong CP problem** in **quantum chromodynamics (QCD)**, which is the study of strong interactions between quarks and gluons.

In the particle world, axions can be thought of as the *introverts*. This is because they are hypothesized to have extremely weak coupling strengths compared to the standard model particles.

They almost never interact with light or regular atoms, passing through entire planets like ghosts through a wall. Because axions are so light, they don't behave like classical point-like particles. Instead, they behave like coherent waves. In the cold vacuum of space, if enough axions gather together, their individual waves begin to overlap and synchronize, creating a rare state of matter called a **Bose-Einstein Condensate (BEC)**. Instead of a star made of individual particles bumping into each other, an axion star is essentially one giant quantum wave, meaning every single particle in the star is doing exactly the same thing at exactly the same time.



Axions are also considered a leading candidate for **cold dark matter** because of their very low velocity dispersion and their extremely weak couplings, implying that these particles behave as cold, collision-less dark matter.

Scientific theories and simulations suggest that when a dense axion star grows too large, or if it passes through the intense magnetic field of a nearby neutron star or magnetar, the axions can be converted into photons. The magnetic field acts like a catalyst, leading to a massive release of energy in the form of transient radio signals. This is proposed to be a possible origin for **Fast Radio Bursts (FRBs)**, which usually last only a few milliseconds.

Fast Radio Bursts (FRBs) are intense, millisecond-long bursts of radio waves from deep space, releasing as much energy in a fraction of a second as the Sun emits over several days. Although their origin is not confirmed, they are thought to be caused by neutron stars, magnetars or other compact objects, often originating in distant galaxies.

PREON STARS: THE MATRYOSHKA DOLL OF THE VOID

For decades, the Standard Model has told us that quarks are fundamental, meaning they are not made of anything else - they are the end of the line. But if we go deeper, preons are hypothetical, point-like subatomic particles proposed as the fundamental building blocks of quarks and leptons. [*Leptons are fundamental, elementary particles that do not participate in strong nuclear interactions, acting as basic building blocks of matter.*]

To understand why this star is an outlaw you have to understand **degeneracy pressure**. This is the force that prevents a neutron star from collapsing. It is a consequence of quantum mechanics arising from the Pauli Exclusion Principle that says two fermions or identical particles (like neutrons) cannot occupy the same space (or same quantum state). At extremely high densities, this produces a pressure that supports white dwarfs and neutron stars against a gravitational collapse or in layman's terms, they "push back" against gravity. But if gravity is strong enough to overcome the push of neutrons, the star collapses into a black hole unless... there is another level of reality underneath.

If quarks are made of preons, then as the quarks are crushed, the preons start pushing back with their own version of degeneracy pressure creating a new, even denser state of matter, nested like a Russian Matryoshka doll. This creates a **Preon Star**: an object so unimaginably dense that it sits right on the event horizon of becoming a black hole, yet still remains a physical object. The density of a preon star is so extreme, that if a neutron star with the mass of the Earth would be about the size of a large stadium, then its corresponding preon star with the mass of the Earth would just be the size of a tennis ball.

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