# SAMPLE

## Cosmos Unveiled: Quark Stars

The Matter Between Neutrons and Black Holes

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# Introduction

A quark star is a hypothetical type of compact, exotic star, where extremely high core temperature and pressure have forced nuclear particles to form quark matter, a continuous state of matter consisting of free quarks. Some massive stars collapse to form neutron stars at the end of their life cycle, as has been both observed and explained theoretically. Under the extreme temperatures and pressures inside neutron stars, the neutrons are normally kept apart by a degeneracy pressure, stabilizing the star and hindering further gravitational collapse.

However, it is hypothesized that under even more extreme temperature and pressure, the degeneracy pressure of the neutrons is overcome, and the neutrons are forced to merge and dissolve into their constituent quarks, creating an ultra-dense phase of quark matter based on densely packed quarks. In this state, a new equilibrium is supposed to emerge, as a new degeneracy pressure between the quarks, as well as repulsive electromagnetic forces, will occur and hinder total gravitational collapse that would form a stellar black hole.

If these ideas are correct, quark stars might occur, and be observable, somewhere in the universe. Numerical simulations of the physics inside neutron stars predict quark deconfinement is likely. Such a scenario is seen as scientifically plausible, but has not been proven observationally or experimentally; the very extreme conditions needed for stabilizing quark matter cannot be created in any laboratory and have not been observed directly in nature.

The stability of quark matter, and hence the existence of quark stars, is for these reasons among the unsolved problems in physics. The analysis about quark stars was first proposed in 1965 by Soviet physicists D. D. Ivanenko and D. F. Kurdgelaidze. Their existence has not been confirmed. The equation of state of quark matter is uncertain, as is the transition point between neutron-degenerate matter and quark matter. Theoretical uncertainties have precluded making predictions from first principles.

Experimentally, the behaviour of quark matter is being actively studied with particle colliders, but this can only produce very hot (above 1012 K) quark-gluon plasma blobs the size of atomic nuclei, which decay immediately after formation. The conditions inside compact stars with extremely high densities and temperatures well below 1012 K cannot be recreated artificially, as there are no known methods to produce, store or study "cold" quark matter directly as it would be found inside quark stars.

The theory predicts quark matter to possess some peculiar characteristics under these conditions. It is hypothesized that when the neutron-degenerate matter, which makes up neutron stars, is put under sufficient pressure from the star's own gravity or the initial supernova creating it, the individual neutrons break down into their constituent quarks (up quarks and down quarks), forming what is known as quark matter. This conversion may be confined to the neutron star's center or it might transform the entire star, depending on the physical circumstances.

Such a star is known as a quark star. Ordinary quark matter consisting of up and down quarks has a very high Fermi energy compared to ordinary atomic matter and is stable only under extreme temperatures and/or pressures. This suggests that the only stable quark stars will be neutron stars with a quark matter core, while quark stars consisting entirely of ordinary quark matter will be highly unstable and re-arrange spontaneously.

It has been shown that the high Fermi energy making ordinary quark matter unstable at low temperatures and pressures can be lowered substantially by the transformation of a sufficient number of up and down quarks into strange quarks, as strange quarks are, relatively speaking, a very heavy type of quark particle.

This kind of quark matter is known specifically as strange quark matter and it is speculated and subject to current scientific investigation whether it might in fact be stable under the conditions of interstellar space (i.e. If this is the case (known as the Bodmer-Witten assumption), quark stars made entirely of quark matter would be stable if they quickly transform into strange quark matter. Stars made of strange quark matter are known as strange stars.

These form a distinct subtype of quark stars. Theoretical investigations have revealed that quark stars might not only be produced from neutron stars and powerful supernovas, they could also be created in the early cosmic phase separations following the Big Bang. If these primordial quark stars transform into strange quark matter before the external temperature and pressure conditions of the early Universe makes them unstable, they might turn out stable, if the Bodmer-Witten assumption holds true. Such primordial strange stars could survive to this day.

Quark stars have some special characteristics that separate them from ordinary neutron stars. Under the physical conditions found inside neutron stars, with extremely high densities but temperatures well below 1012 K, quark matter is predicted to exhibit some peculiar characteristics. It is expected to behave as a Fermi liquid and enter a so-called color-flavor-locked (CFL) phase of color superconductivity, where "color" refers to the six

"charges" exhibited in the strong interaction, instead of the two charges (positive and negative) in electromagnetism.

# Chapter 01: The Discovery of Quark Stars

Under such conditions the theory expects quark matter to behave in ways no ordinary substance can, and a star built of the stuff is what the chapters of this book call a quark star. At slightly lower densities, corresponding to higher layers closer to the surface of the compact star, the quark matter will behave as a non-CFL quark liquid, a phase that is even more mysterious than CFL and might include color conductivity and/or several additional yet undiscovered phases.

None of these extreme conditions can currently be recreated in laboratories so nothing can be inferred about these phases from direct experiments. At least under the assumptions mentioned above, the probability of a given neutron star being a quark star is low, so in the Milky Way there would only be a small population of quark stars.

If it is correct, however, that overdense neutron stars can turn into quark stars, that makes the possible number of quark stars higher than was originally thought, as observers would be looking for the wrong type of star.

A neutron star without deconfinement to quarks and higher densities cannot have a rotational period shorter than a millisecond; even with the unimaginable gravity of such a condensed object the centrifugal force of faster rotation would eject matter from the surface, so detection of a pulsar of millisecond or less period would be strong evidence of a quark star.

Observations released by the Chandra X-ray Observatory on April 10, 2002, detected two possible quark stars, designated RX J1856.5-3754 and 3C 58, which had previously been thought to be neutron stars. Based on the known laws of physics, the former appeared much smaller and the latter much colder than it should be, suggesting that they are composed of material denser than neutron-degenerate matter.

However, these observations are met with skepticism by researchers who say the results were not conclusive; and since the late 2000s, the possibility that RX J1856 is a quark star has been excluded. Another star, XTE J1739-285, has been observed by a team led by Philip Kaaret of the University of Iowa and reported as a possible quark star candidate. In 2006, You-Ling Yue et al., from Peking University, suggested that PSR B0943+10 may in fact be a low-mass quark star.

It was reported in 2008 that observations of supernovae SN 2006gy, SN 2005gj and SN 2005ap also suggest the existence of quark stars. It has been suggested that the collapsed core of supernova SN 1987A may be a quark star.

In 2015, Zi-Gao Dai et al.

Jaffe 1977 suggested the H dibaryon, a six-quark state with equal numbers of up-, down-, and strange quarks (represented as uuddss or udsuds). Bound multi-quark systems with heavy quarks (QQqq). In 1987, a pentaquark state was first proposed with a charm anti-quark (qqqsc). Pentaquark state with an antistrange quark and four light quarks consisting of up- and down-quarks only (qqqqs). Light pentaquarks are grouped within an antidecuplet, the lightest candidate, the Theta-plus pentaquark, which can also be described by the diquark model of Robert L.

Whitfield, John (April 2002). Nature. ISSN 0028-0836. CERN Courier. June 2002.

The ratio between the nebula's size and the expansion velocity of its filaments provides an estimate for the nebula's lifetime, which exceeds the pulsar's age by a factor of ten.)

In 2022 it was suggested that GW190425, which likely formed as a merger between two neutron stars giving off gravitational waves in the process, could be a quark star. Apart from ordinary quark matter and strange quark matter, other types of quark-gluon plasma might hypothetically occur or be formed inside neutron stars and quark stars. This includes the following, some of which have been observed and studied in laboratories: Robert L. Jaffe 1977, suggested a four-quark state with strangeness (qsqs). Robert L.

Strange stars might exist without regard to the Bodmer-Witten assumption of stability at near-zero temperatures and pressures, as strange quark matter might form and remain stable at the core of neutron stars, in the same way as ordinary quark matter could. Such strange stars will naturally have a crust layer of neutron matter. The depth of the crust layer will depend on the physical conditions and circumstances of the entire star and on the properties of strange quark matter in general.

Stars partially made up of quark matter (including strange quark matter) are also referred to as hybrid stars. The collapse of the crust layer of strange stars is one of the proposed causes of fast radio bursts. Neutron stars are formed when the collapse of a star occurs with such intense force that gravity forces subatomic particles such as protons and electrons to merge into neutrally charged neutron particles, releasing a shower of neutrinos.

If the resultant neutral core is able to maintain form and not collapse into a black hole, the result is an incredibly dense celestial body composed almost entirely of uncharged particles. Protons and neutrons are composed of three quarks: a proton by two up quarks and one down quark, a neutron by two down quarks and one up quark.

It is hypothesized that within neutron stars, the conditions are so extreme that a process known as deconfinement occurs: where subatomic particles dissolve and leave their constituent quarks behind as free particles. The temperature and pressure would then force these quarks to be squeezed together to such an extent that they would form a hypothetical phase of matter known as quark matter. If this occurs, the neutron star becomes a "quark star".

Cramer, John G.: "Quark Stars, Alternate View Column AV-114", Analog Science

Fiction & Fact Magazine, November 2002

A strange star, also called a strange quark star, is a hypothetical compact astronomical object, a quark star made of strange quark matter.

If the pressure is great enough, the quarks could be affected even further and a portion could transform into strange quarks, which would then interact with the other "non-strange" quarks to form strange matter. If this occurs, the quark star would then become a strange star. Early work on strange quark matter suggested that it would be a homogeneous liquid, but other models propose a heterogeneous alternative with positively charged "strange quark nuggets" embedded in a negatively charged electron gas.

This structure decreases the stars' external electric field and density variation from previous theoretical expectations, with the result that such stars appear nearly indistinguishable from ordinary neutron stars. Other theoretical work contends that:A sharp interface between quark matter and the vacuum would have very different properties from the surface of a neutron star.

Addressing key parameters like surface tension and electrical forces that were neglected in the original study, the results show that as long as the surface tension is below a low critical value, the large strangelets are indeed unstable to fragmentation and strange stars naturally come with complex strangelet crusts, analogous to those of neutron stars. For a strange star's crust to collapse, it must accrete matter from its environment in some form.

The release of even small amounts of its matter causes a cascading effect on the star's crust. This is thought to result in a massive release of magnetic energy as well as electron-positron pairs in the initial phases of the collapsing stage.

This release of high-energy particles and magnetic energy in such a short period of time causes the newly released electron-positron pairs to be directed towards the poles of the strange star due to the increased magnetic energy created by the initial secretion of the strange star's matter. Once these electron-positron pairs are directed to the star's poles, they are then ejected at

relativistic velocities, which is proposed to be one of the causes of fast radio bursts.

A fair reading of the hypothesis should begin by naming the room it lives in, which is the widest gap in laboratory physics. A neutron star's core sits at several times the density at which ordinary nuclear matter saturates, a pressure regime no collider and no bomb can reproduce at low temperature, and the theory of nuclear matter in that room is interpolation rather than knowledge, the measured points left far behind as the density climbs. The quark matter hypothesis is the candid admission that the room exists and that its contents are unknown: physicists can state what quarks are with great confidence, can state the equations that govern them in principle, and cannot solve those equations in the cold, dense conditions a compact star supplies. Everything in this book lives inside that honesty, because the discovery being waited for is the first direct evidence of what fills the widest unlit room in physics.

The room has a ceiling with a name. The same relativistic mechanics that caps white dwarfs at the Chandrasekhar mass caps neutron stars too, at a limit set by the unknown stiffness of the interior's matter, and the ceiling's modern estimate spans a band wide enough to hide a quark phase or to exclude one. A transition to quark matter is one of the few mechanisms that could move the ceiling, either upward, because a new source of pressure resists the crush, or downward, because a soft new phase gives way, and the observation of neutron stars sitting near two solar masses has therefore become the field's favorite arbiter: any interior recipe soft enough to convert easily must still be stiff enough to carry that weight, and the tension between those two demands is where the hypothesis now lives.

End of free sample. The full book is available at putrabooks.github.io

# ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.