Could Strange Quark Matter Serve as an Alternative to Dark Matter?

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I. Abstract

This paper discusses whether strange quark matter (SQM) would mathematically serve as an alternative to dark matter. This paper aims to prove that SQM cannot suffice for dark matter because there will not be enough SQM. By evaluating data regarding the masses of strange quark stars, calculating the amount of SQM in the universe, and evaluating its effect on the scale of the universe, this paper will determine whether this is true or not.

II. Introduction

Strange quark matter

All matter is made of quarks. Each quark is assigned a color (unrelated to the electromagnetic spectrum) that confines them into hadrons accordingly. When exposed to extreme pressure and heat, the quarks ignore their color and deconfine.[1] This deconfined mass of quarks is called quark matter. Quark matter cannot be made of more than three flavors because charm, top, and bottom quarks are all too unstable to exist on their own. SQM is a mass of deconfined up, down, and strange quarks that are perfectly stable. Because SQM exists in a perfectly stable state, all other matter is compelled to exhibit the same properties, thus also becoming SQM.[2] Two flavor quark matter is less favorable to three-flavor quark matter because three-flavor quark matter's strangeness value is less than two flavor quark matter. Strangeness is defined as the number of strange quarks or antistrange quarks within any form of matter.[3] Strangeness determines the decay rate of particles with this property, and thus the stability of them.[4]

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[1] Weincheng, Lv. n.d. Accessed January 19, 2020. http://guava.physics.uiuc.edu/~nigel/courses/563/Essays_2008/PDF/lv.pdf.

[2] Alcock, Charles, Edward Farhi, and Angela Olinto. n.d. http://adsabs.harvard.edu/full/1986ApJ...310..261A.

[3] "Strangeness." The Free Dictionary. Farlex. Accessed January 29, 2020. https://www.thefreedictionary.com/strangeness.

[4] "Quarks." n.d. Quarks. Accessed January 19, 2020. http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/quark.html

The formation and properties of Neutron Stars

Neutron stars are formed when a massive dying star collapses on itself. A star burns through elements in the following order: hydrogen, helium, oxygen, carbon, silicon, and iron. The rapidly increasing temperature of a star breaks the iron in its core down to helium, then into protons and neutrons. This reaction requires such an amount of energy that the core must collapse for it to be provided.[5] If a collapsing star's core has a mass of 8 to 30 solar masses (1 solar mass is the mass of the sun), it will become a neutron star; if it has a mass greater than 30 solar masses, it will become a black hole.[6] The collapse of the original star into a super-dense neutron star causes the collision of every proton and electron, which causes emissions of electron neutrinos and the formation of neutrons.[7] Due to the Pauli Exclusion Principle, neutrons tend to repel other neutrons, and protons tend to repel other protons; thus, the neutron star's immense gravitational pull is alleviated on the subatomic level, preventing total collapse.[8]

Strange Quark Stars

Quark stars form when gravity becomes strong enough to compress the nucleons of the neutron star so that their quarks deconfine. As there is even less space between particles, the former neutron star reaches a density of about 10^{19} kgm^{-3}.[9] For perspective, the average neutron star has a density of about 10^{17} kgm^{-3}.[10] The core of a strange quark star is made of SQM.[11] When two of these strange quark stars

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5 . 1969CoASP...1..172C Page 172. Accessed January 19, 2020. http://adsabs.harvard.edu/full/1969CoASP...1..172C.

6 "Introduction to Neutron Stars." Neutron stars. Accessed January 29, 2020. https://www.astro.umd.edu/~miller/nstar.html.

7 "Quark Stars." n.d. altvw114. Accessed January 19, 2020. https://www.npl.washington.edu/AV/altvw114.html.

8 Ibid.

9 Sandin, Frederik, n.d.

10 "Neutron Star: COSMOS." n.d. Centre for Astrophysics and Supercomputing. Accessed January 19, 2020. http://astronomy.swin.edu.au/cosmos/N/Neutron Star.

11 Snell, Carly. n.d. Accessed January 19, 2020. http://hosting.astro.cornell.edu/~dong/a6511/presentations/SnellQuarkStarReport.pdf.

collide, they may scatter some of the SQM in their core. In doing this, they release tiny drops of strange matter called strangelets.[12] The density of these droplets may account for dark matter. This paper aims to explore how there will not be enough of these strangelets in the universe to suffice as an alternative to the theory of dark matter.

III. Research

Sources of SQM: The Big Bang

Strangelets expelled from the insides of neutron stars during collisions or leftovers from the big bang may suffice as an alternative to the theory of dark matter. Strangelets' dense nature means a large quantity of mass can go undetected, bar gravitational interaction. This property of strangelets allows them to be a candidate for dark matter. The only potential issue would be the number of strangelets in the universe, as non-baryonic dark matter composes 85% of all matter in the observable universe.[13] To consider strangelets as a substitute for dark matter, one must take into account the amount possible in the universe. Some SQM was created during the dawn of the universe.

The observable universe has a mass of about 6×10^{54} g. The density two flavor quark matter, or quark-gluon plasma (QGP), needs to exist is 10^{13} gcm^{-3}. This density is the lowest density QGP can be without it beginning to cool. Therefore, after the universe was greater than 10^{9}km in diameter, QGP began to cool. The universe's expansion is defined by the Hubble parameter, 72 kms^{-1} per megaparsec, or $2.186 \times 10^{21} km^2/s$. QGP had approximately 1.52×10^{-13} seconds to exist before it cooled (A.1). The law of conservation of strangeness[14] would mean strange quarks and their antimatter counterparts would have been created. All the strangeness in the universe was condensed down to this small point, thus SQM must

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[12] Wiktorowicz, G., A. Drago, G. Pagliara, and S.B. Popov. n.d. Accessed January 19, 2020. https://arxiv.org/pdf/1707.01586.pdf.

[13] Pearson, Chris. 2003. February 11, 2003. https://www.ir.isas.jaxa.jp/~cpp/teaching/cosmology/documents/cosmology01-05.pdf.

[14] "Quarks." n.d. Quarks. Accessed January 19, 2020. http://hyperphysics.phy-astr.gsu.edu/hbase/Particles/quark.html

have existed. SQM is supposedly the base state of all matter, yet QGP is speculated to have been the first form of matter in the universe.[6] Some of this SQM may have formed strange quark stars. These primordial stars are included in Figure 1.

Sources of SQM: Strange Quark Stars

The main source of SQM in the universe is strange quark stars. As explained in the introduction, strange quark stars are created from higher mass neutron stars. The formation of neutron stars is fairly common, as the core of its precursor star has to be 3 to 30 solar masses. Because the most massive star in Fig. 1 is approximately 75.85 solar masses, that leaves a considerable amount of stars to be eligible to become neutron stars upon their death. One must consider the distribution of stellar masses in calculating the probability of a neutron star's formation, as stars with certain masses are more common than others. The distribution of individual masses of stars from an index of 5227 stars[15] is shown in Figure 1.

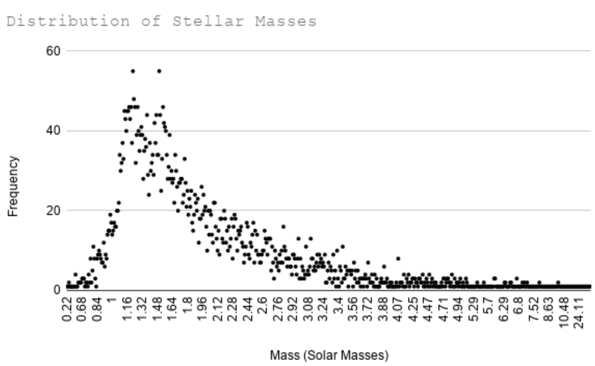

Fig. 1 - A scatterplot of the masses of stars from an index of 5227[16]

The diameter of a speculated quark star (RXJ1856)[17] is 11$\pm$4km and the density is 10^{13} gcm^{-1}.[18] Therefore, the mass can be calculated to be between 8.88 and 9.02 solar masses. The trendline of this data can be defined by the piecewise function:

$$\left\{y = 55.6e^{-0.00772x}, \qquad 1.16 \le x \le 75.85\right\}$$

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15 "Star Database." n.d. VizieR. Accessed January 24, 2020. https://vizier.u-strasbg.fr/viz-bin/VizieR.

16 Ibid.

17 Drake, Marshall, Dreizler, Freeman, Juda, Kashyap, Nicastro, Pease, Werner, and K. 2002. "Is RX J185635-375 a Quark Star?" ArXiv.org. April 9, 2002. https://arxiv.org/abs/astro-ph/0204159.

18 "Quark Stars." n.d. altvw114. Accessed January 19, 2020. https://www.npl.washington.edu/AV/altvw114.html.

$$\{y = 0.1329e^{4.6466x}, \qquad 0 < x < 1.16\}$$

Using the functions of this data, one can find the probability of a quark star formation by taking

$$P_n = \frac{\int_{8.8847}^{9.0295} 55.6e^{-0.00772x}}{\int_{0}^{1.16} 0.1329e^{4.6466x} + \int_{1.16}^{75.85} 55.6e^{-0.00772x}},$$

which gives us the area under the curve within the domain of masses needed for a quark star formation, divided by the total area under the trendline. When simplified,

$$P_n = \frac{7.9222}{3134.1006} = 0.00252\times100 = 0.252$$

This means 0.252% of the 5227 stars listed in Fig. 1 are viable candidates for quark stars. Applying this percentage to the scale of the universe[19], which is 10^{21} stars, there are 2.5×10^{18} eligible candidates for quark stars. By multiplying the average mass of a quark star by the number of candidates, there are $2.2592\times10^{19}\pm1.95\times10^{17}$ solar masses worth of quark matter in the universe. Though the mass of all quark matter in the universe may be large, only some of it may be stable. Since strange matter is conjected to be the ground state of matter,[20] these stars will tend to become strange quark stars; thus, the amount of strange matter in the stars of the observable universe is $2.2592\times10^{19}\pm1.95\times10^{17}$ solar masses.

The Amount of SQM in the Universe

SQM cannot be viewed as a candidate for dark matter if it does not gravitationally interact with other celestial bodies, and SQM cannot interact with other celestial bodies if it is contained within a

[19] . UCSB Science Line. Accessed January 25, 2020. https://scienceline.ucsb.edu/getkey.php?key=3775.

[20] Alcock, Charles, Edward Farhi, and Angela Olinto. n.d. http://adsabs.harvard.edu/full/1986ApJ...310..261A.

strange star. Stellar collisions occur once every 100,000 years in a single globular cluster of a galaxy.[21] Since there are 10^{10} galaxies in the observable universe, each on average with 30 globular clusters, Stellar collisions occur about 3×10^{8} times per year. Because 0.25277% of all stars are theorized to be quark stars, stellar collisions in which at least one of the stars involved are quark stars occur 758,310 times a year. Bear in mind that scientists have not detected these collisions as they are on the scale of the entire observable universe. Instruments used by these scientists do not have the capability of detecting every stellar collision.

The mass loss in stellar collisions is about 1-10% per star.[22] As represented in figure 1, most stars in the universe have a lesser mass than quark stars, so it is highly unlikely that a quark star will be completely enveloped by a giant star, as they are fairly uncommon. Given that the only significant star in the collision being analyzed is the quark star, and the average mass of a quark star is 8.9886 solar masses, the total SQM expelled during a single collision is, on average, 0.09 to 0.89 solar masses. Extrapolating this upon every collision in the observable universe, 6.8×10^{4} to 6.8×10^{5} solar masses of SQM has been expelled from stars and is floating freely in space. For mathematical purposes, the average of the two values, 3.7×10^{5} solar masses, will be used (A.2).

Dark Matter and SQM: A Mathematical Experiment

[21] Chang, Kenneth. 2000. "Two Stars Collide; a New Star Is Born." The New York Times. The New York Times. June 13, 2000. https://archive.nytimes.com/www.nytimes.com/library/national/science/061300sci-stars-collisions.html.

[22] Davies, Melvyn B. n.d. Accessed January 26, 2020. http://www.astro.lu.se/~melvyn/mbdaviespraguetalk.pdf.

It is theorized that dark matter makes up 85% of all matter in the observable universe. [23] This is found by calculating the density parameter Ω of all baryonic matter Ω_0. There are several different types of matter in the universe. All matter currently calculated has a Ω_0 of 0.27.[24] WMAP has determined that the universe is planar[25], so Ω_0 must equal one. In this proof, $\Omega_{0m} + \Omega_s = 1$, where Ω_s represents the density parameter of SQM and Ω_{0m} represents the density parameter of all baryonic matter. Using equation A.3, The critical density is calculated to be 9.01×10^{12}. Solving for the density of strange matter throughout space is more convoluted than finding the density of a regular object, as the universe is constantly expanding. Therefore, using the radius of the observable universe, $1.7\times10^{26} \pm 20\%$ m,[26] the volume of the observable universe is $2.06\times10^{79} \pm 20\%$ m. The data used in Fig. 1 is comparable to the entire observable universe, so the mass of the amount of SQM calculated previously, 3.74×10^{5}solar masses, is assumed. This outputs a matter density of 3.6196×10^{-44} kgm^{-3}.

Using these values coupled with equation A.4,

$$\Omega_s = \frac{3.6196\times10^{-44}}{9.0158\times10^{12}} = 4.0146\times10^{-57}$$

This value is much less than the density parameter of dark matter: 0.226.[27]

[23] 2003. Accessed January 26, 2020. http://www.star.bris.ac.uk/sxp/coslecture3.pdf.

[24] “Density Parameter, Ω.” Density Parameter, Omega. Accessed January 29, 2020. http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/denpar.html.

[25] “WMAP- Content of the Universe.” n.d. NASA. NASA. Accessed January 26, 2020. https://wmap.gsfc.nasa.gov/universe/uni_matter.html.

[26] “Mass, Size and Density of the Universe.” n.d. Mass, Size, and Density of the Universe. Accessed January 26, 2020. https://people.cs.umass.edu/~immerman/stanford/universe.html.

[27] “Density Parameter, Ω.” Density Parameter, Omega. Accessed January 29, 2020. http://hyperphysics.phy-astr.gsu.edu/hbase/Astro/denpar.html.

IV. Conclusion

The density parameter of SQM was found to be insignificant on the scale of the observable universe, as there is not a high enough density parameter of SQM for it to be comparable to dark matter. However, SQM is still a useful concept. As discussed in this paper, some of it may have formed at the dawn of the universe, shortly after the big bang. Discovery and study of this primordial material would provide insight as to how the universe was seconds after it came into existence and an effective way to better understand the properties of sub-nuclear particles and the laws of quantum mechanics. The search for dark matter continues as SQM can now no longer be considered an alternative to dark matter.

V. Appendix

A.1 - The computations shown display the size the universe was before QGP was able to cool, then the time window in which QGP existed.

$$V = \frac{m}{\rho} = \frac{6\times10^{54}\, g}{10^{13}\, gcm^{-3}} = 6\times10^{41} cm^{3}$$

Volume to the diameter of the observable universe:

$$6\times10^{41} = \frac{4}{3}\pi r^{3} \rightarrow \frac{\frac{3}{4}(6\times10^{41})}{\pi} = r^{3} \rightarrow 5\times10^{8}\, km = r \rightarrow d = 2r = 10^{9}\, km$$

Kinematics of the expanding universe:

$$\Delta x - \frac{3}{2}at = v_{i}$$

$$5\times10^{8} - \frac{3}{2}(2.186\times10^{21})t = 0$$

$$5\times10^{8} = (3.279\times10^{21})t$$

$$1.52\times10^{-13}\, seconds = t$$

A.2 - These computations show the amount of SQM in the universe that is not strangelets

Higher end (assumes 10% loss)

$$\frac{8.88+9.02}{2}\times 10\% = 0.89$$

$$0.89\times 758310 = 674896$$

Lower end (assumes 1% loss)

$$\frac{8.88+9.02}{2}\times 1\% = 0.09$$

$$0.09\times 758310 = 68248$$

Average of 10% and 1% loss

$$\frac{674896+68248}{2} = 371572$$

A.3 - The equation and method used to find the critical density of the universe are shown, where H is the Hubble parameter and G is the universal gravitational constant.

$$\rho_c = \frac{3H^2}{8\pi G}$$

$$\rho_c = \frac{15123}{0.000000001677} = 9.01\times 10^{12}\ \text{kgm}^{-3}$$

A.4 - The equation used to calculate the density parameter Ω_0 is shown

$$\Omega_0 = \frac{\rho_0}{\rho_c}$$