Powering Starships with Compact Condensed Quark Matter

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Abstract

Compact Composite Objects (CCOs), nuggets of dense Color-Flavor-Locked Superconducting quark matter created before or during the Quantum Chromo-Dynamics phase transition in the early universe[1, 2, 3], could provide a natural explanation for both Dark Matter (DM) and the observed cosmological baryon asymmetry[4, 5, 6], without requiring modifications to fundamental physics. This hypothesis implies a relic CCO population in the Solar System, captured during its formation, which would lead to a population of "strange asteroids," bodies with mm-radii quark matter cores and ordinary matter (rock or ice) mantles. This hypothesis is supported by the observed population of small Very Fast Rotating (VFR) asteroids (bodies with rotation periods as short as 25 sec); the VFR data are consistent with a population of strange asteroids with core masses of order 10^{10} - 10^{11} kg. If the VFR asteroids are indeed strange asteroids their CCO cores could be mined using the techniques being developed for asteroid mining. Besides being intrinsically of great scientific interest, CCO cores could also serve as very powerful sources of energy, releasing a substantial fraction of the mass energy of incident particles as their quarks are absorbed into the QCD superfluid. Through a process analogous to Andreev reflection in superconductors[7], even normal matter CCOs could be used as antimatter factories, potentially providing as much as 10^9 kg of antimatter per CCO. While of course speculative, this energy source, if realized, would be suitable for propelling starships to a substantial fraction of the speed of light, and could be found, extracted and exploited in our Solar System with existing and near-term developments in technology.

CCOs as Dark Matter

Dark matter, first proposed 8 decades ago to reconcile the observed velocities and luminosities of galactic clusters[8, 9], is now thought to make up about 27% of the energy density of the universe[10]. This cosmic element can be shown to be cold (i.e., with low velocity dispersion) in the early universe, and is thus commonly denoted Cold Dark Matter (CDM). There are numerous proposals invoking various forms of new physics to explain CDM (typically through new fields and particles with very weak interactions with ordinary matter) but, despite decades of work, the nature of CDM remains a mystery.

The idea that condensed quark matter could form in the early universe and persist until the present has a considerable history, first proposed as strangelets[11] and nuclearites[12] almost 3 decades ago. CCOs are thus a new variant of an old idea. Compact quark objects would represent a bound state of matter left over from the epoch before the QCD phase transition, when the the density was $> 4 \times 10^{17}$ kg m^{-3} (the nuclear density). Recent work indicates that at low temperatures and high densities the lowest QCD energy state is Color-Flavor-Locked (CFL) superconducting quark matter[1, 2, 13, 14, 15, 16]. CFL quark matter may be stable at zero temperature, and could in fact be the fundamental state of matter, both more stable than ^{56}Fe and more prevalent than ordinary hadronic matter. CCOs would be consistent with the observational constraints on CDM not through new physics and weak interactions, but through their very small cross sections; CCOs in Deep Space are physically small enough to evade the existing cross-section limits by many orders of magnitude.

Condensed matter nuggets are generally assumed to form during a first-order phase transition in the early universe[11]. In the theory derived by Zhitnitsky and his colleagues CCOs are created by the collapse of axion domain walls[1, 4, 5, 17, 18, 19] in the first few microseconds after the Big Bang. The axion domain wall theory bounds the primordial CCO mass, M$_{CCO}$, to a range of a little over an order of magnitude in mass, with the mid-point of the range being set by the value of the axion decay constant, f$_a$, and the range reflecting the need for a CCO to be both energetically favorable and have greater than nuclear density. The experimental constraints on the axion decay constant are sufficiently broad that they dominate the theoretical uncertainty in the primordial CCO mass; current experimental limits[20] on f$_a$ limit primordial CCO masses to the range 10^5 kg $\lesssim$ M$_{CCO}$ $\lesssim 4 \times 10^{10}$ kg. Figure 1 shows that this mass range is not excluded by any experimental data and that the Solar System asteroid data are consistent with upper end of this range, suggesting the axion decay constant lies within the upper end of its current experimental constraints.

Strange Asteroids in the Solar System

Planetary systems such as the Solar System appear to result from the gravitational collapse of cold molecular clouds subject to supersonic turbulence in the InterStellar Medium (ISM), with interacting shock-waves causing density perturbations exceeding the local critical density[26]. The shocked gas becomes gravitationally unstable, collapses, and fragments, with stellar systems forming out of the condensed fragments. Dark matter would not be directly perturbed by gas pressure changes but it would respond to the gravitational potential changes caused by these fluid motions. A small faction of the dark matter in a molecular cloud would, by chance, be moving slowly enough to be captured by the collapsing cloud as the cloud gravitational potential changes around it, leading to a population of primordially captured dark matter in any resulting planetary system, including in our Solar System.

While this gravitational capture mechanism would apply to most Dark Matter can-

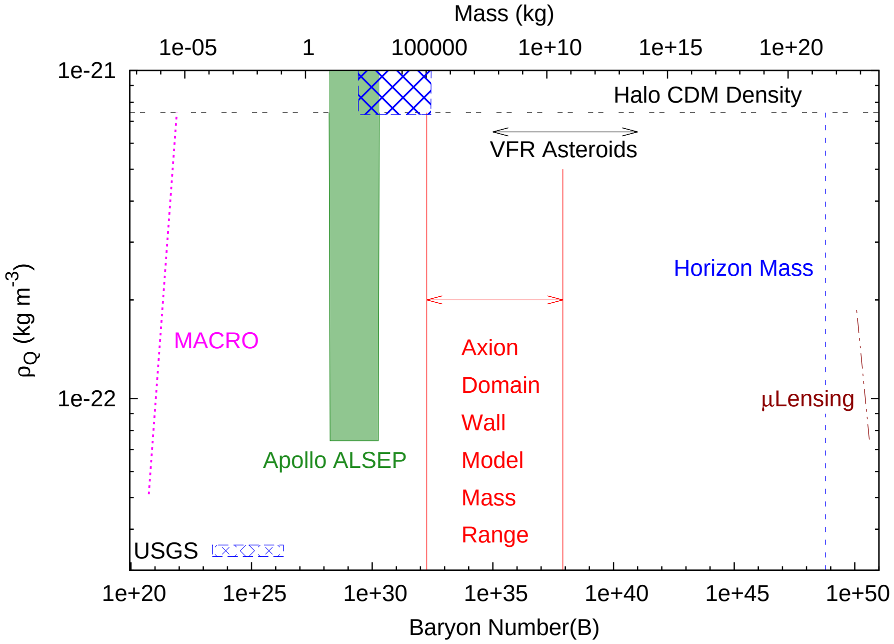

Figure 1: Limits on CCOs as a function of mass, assuming a monochromatic CCO mass spectrum. The experimental "asteroid constraints" and the theoretical "axion domain wall mass range" are included regions, which do not conflict with any of the other, experimentally excluded, mass ranges. The MACRO[21] constraints apply to the left of the indicated curves, and the Horizon Mass[22] and μlensing constraints[23] apply to the right of the indicated curves. (The MACRO limit is a flux limit converted to a minimum mass density assuming that the Galactic Halo dominates the CCO flux, the local Halo CDM density applies to the solar system, and the Halo velocity, v_{Halo}, is 220 km sec^{-1}.) The Apollo and USGS seismological constraints[24] exclude the shaded regions. The Halo CDM Density is from local stellar kinematics[25].

didates, CCO Dark Matter would actively influence subsequent events, for example by serving as high mass-to-area-ratio planetesimal nucleation sites, and thus potentially resolving the "meter barrier" issue[27, 28, 29] in planetary formation. Most of the primordially captured CCOs would, after taking part in planetary formation, now reside at the center of the Sun, planets and smaller bodies, where they would be inaccessible for direct study and exploitation, Given the relatively small total mass predicted for primordial CCOs in the Solar System, massive bodies such as the Earth would have a small fraction of their mass in a physically small CCO core; the Earth, for example, would have about 3×10^{-5} of its total mass residing in an ~ 4 m radius strange matter sphere at its center, assuming that the condensed matter is distributed proportionally to the mass of the host body.

A possible method to detect and study CCOs is neutrino radiography[30] of the Earth's core. A neutrino beam could be aimed from a terrestrial accelerator directly down at the center of the core; the dense quark matter in a 4 m central core would cast an ~ 8 m radius neutrino shadow at the accelerator's antipode. Current neutrino beam alignment accuracy[31] is ~ 50 μradians, or about 600 m at the antipode of the accelerator, implying an optimal beam collimation of order 50 μradians, to ensure that the CCO in the core would be illuminated by the beam. A neutrino telescope placed at the exact antipode could confirm the existence of a CCO core, measure the amount of neutrino absorption by the strange matter in the core, and detect CCO core Slichter modes, if these are excited to many meter amplitudes.

The best near-term method to detect and study CCOs appears to be search for ones embedded in the centers of small asteroids; such CCOs, if found, could be studied directly by spacecraft. CCOs are thought to be stable against shrinkage at low energies, implying a definite lower limit to CCO core masses in the Solar System. Sufficiently small asteroids, with radii $\lesssim 100$ meters, would thus, if they have a CCO core at all, be "strange asteroids," with a large part of their total mass provided by strange quark matter. This additional mass could greatly increase their apparent bulk density, potentially to values $\gg$ the density of Osmium (the densest stable element, with ρ = 22587 kg m^{-3}), considerably simplifying their detection from astronomical observations.

Observational Constraints on the Mass of Strange Asteroids

The most straightforward way to conclusively find strange asteroids would be to find objects with densities greater than that of Osmium, through the determination of the size and mass of small asteroids. Although is straightforward to estimate the size of an asteroid from its distance and luminosity, it is hard to remotely determine the mass of small bodies without either the discovery of a natural satellite or *in situ* spacecraft exploration. There are very few binary orbits known for asteroids smaller than 200 m in radius, and the smallest asteroid visited by spacecraft is the roughly 500 meter long (25143) Itokawa. It is thus necessary to use indirect methods to estimate the mass of small asteroids; one such method is provided by the rotation of the asteroids.

Radiation forcing is important for small asteroids in the Main Belt and the inner

Solar System, with forcing in linear momentum being described by the Yarkovsky effect[32], and radiative torques by the Yarkovsky-OKeefe-Radzievskii-Paddack (YORP) effect[33]. Many small and medium sized asteroids are apparently spun up by YORP and rotate near or at their limit rotation[34], the rotation rate where objects on the equator are no longer gravitationally bound. For a strange asteroid with a centrally located core, while the mass would be greatly increased compared to that of a similarly sized ordinary-matter asteroid, the increase in the moments of inertia due to the core would be negligible. This implies that strange asteroids should have small orbital changes from the Yarkovsky effect, but could be greatly spun-up (or down) by YORP torques. For bodies where the CCO core dominates the total mass, the core gravity will hold the mantle together against rotational disruption, allowing small strange asteroids to withstand higher spin rates than similar-sized ordinary matter bodies. As the maximum spin rate before rotational disruption depends on a body's density and tensile strength, asteroid rotation data, together with a tensile strength model, can be used as a proxy to determine densities.

Figure 2 reveals something of the complicated relationships[35, 36, 34] between asteroid radii and rotation periods, using the complete set of rotation data available as of November, 2012[37, 38]. The asteroids can be usefully divided into three separate rotational regimes for different radius ranges. Asteroids with radii $\mathrm{R}_A > 50$ km include both Main Belt and outer solar system objects and have, with one exception, rotational periods between 3 and 60 hours. Asteroids with 200 m $< \mathrm{R}_A \leq 50$ km are predominately Main Belt and Near Earth Objects (NEO) displaying a wide variety of rotation periods, including both very long period rotators and a large number of bodies near a limiting period of about 2.2 hours[35]. Finally, "small" bodies with $\mathrm{R}_A \leq 200$ m are mostly (85%) NEO and include many fast rotating bodies; the shortest rotation period, that of 2010 JL88, being only 25 seconds.

The limiting period of $\sim$2.2 hours visible in Figure 2 is generally thought to reflect a "Rubble Pile Limit," (RPL), the period at which the equatorial rotational acceleration cancels the gravitational acceleration on the body's equator, implying the loss of unattached surface mass and the beginning of aurface rotational disruption. For a spherical ordinary matter body (denoted by subscript "A") with uniform density ρ rotating at a frequency, Ω, mass loss would begin at the rotational RPL frequency, Ω_{RP}, with

$$\Omega_{RP}^2 = \frac{GM_A}{R_A^3} = \frac{4\pi G\rho_A}{3} \tag{1}$$

Equation 1, together with the apparent RPL rotation limit of 2.2 hours, implies a bulk asteroid $\rho_A \sim 2300$ kg m^{-1}, within the uncertainty of the average density of the common S type (stony) asteroids [39]. Based on Equation 1 the asteroids can be usefully divided into rotation classes, with "Fast Rotators" (or FR) asteroids being those with periods $<$ the apparent RPL of 2.2 hours, "Very Fast Rotators" (or VFR) being those bodies with periods $<$ the RPL for a solid sphere with the density of Osmium (0.6 hours), and all other asteroids being considered to be "slow rotators." (Note that while small slow rotators may well have a condensed matter core, there is no way to distinguish between strange and ordinary matter slow rotators purely on the basis of rotation rate.)

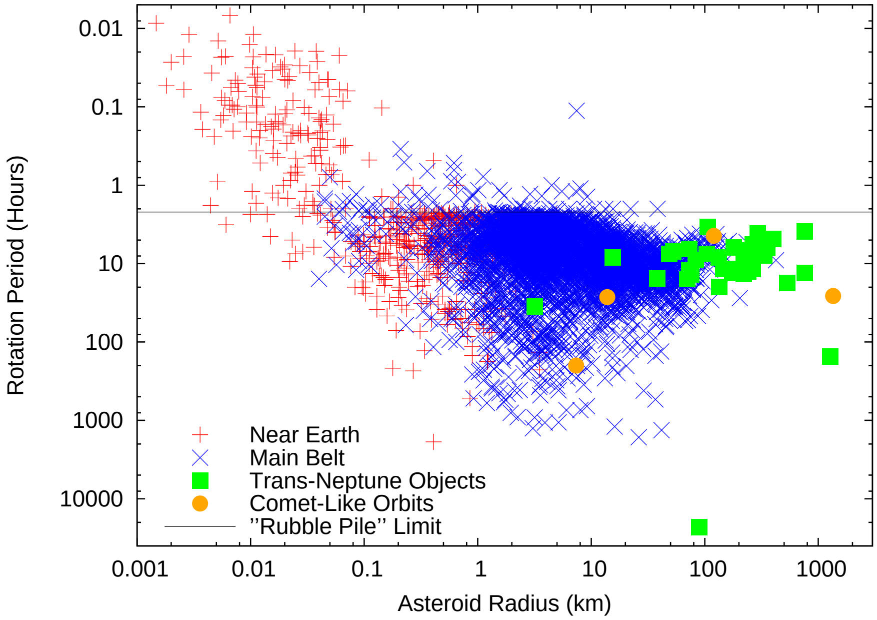

Figure 2: The asteroid rotation period-radius relation for all 5077 bodies with rotation and radius data, based on the November 2012 Asteroid Light Curve Database[37], after the removal of any flagged data. The Hungaria and Mars Crossing asteroids are included in the Main Belt asteroid category in this image. The change in the character of asteroid rotation rates at R ~ 200 m is obvious to the eye, with many asteroids with R < 200 m having rotation periods < 1 hour and almost all asteroids with R > 200 m having periods $\gtrsim 2$ hours. The "Rubble Pile" limit of Equation 1 is also shown.

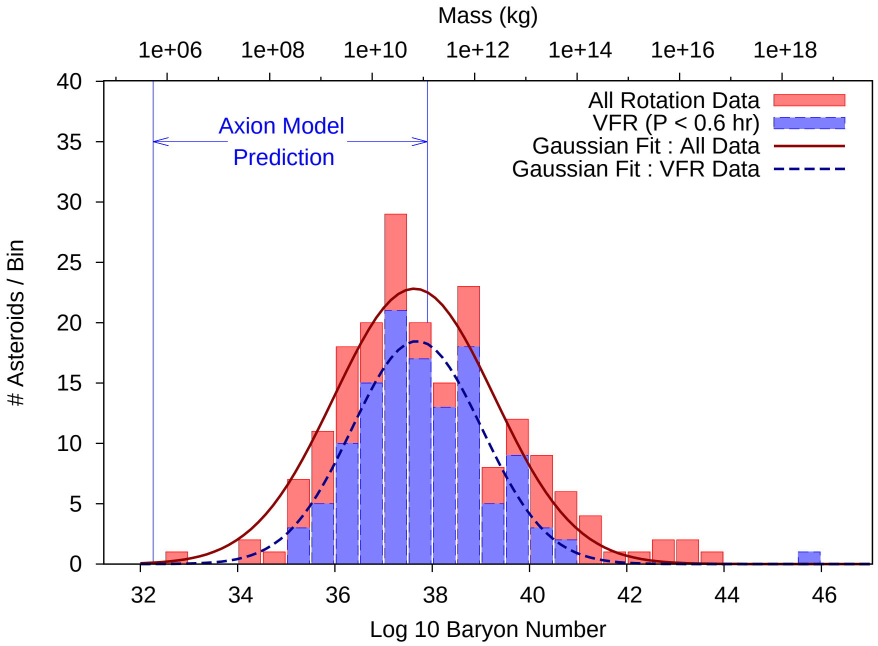

Figure 3: The number of candidate strange asteroids as a function of the CCO core mass required to prevent rotational disruption, assuming gravitational binding only. Estimates are provided from asteroid rotation data referenced to a rubble pile model with a default ρ = 2300 kg m^{-3} for all of the rotation data (“All Rotation Data”) and in addition for the Very Fast Rotation asteroid subset (“VFR data”). Also shown (as vertical lines) is the CCO mass predicted by the axion domain wall theory. The displayed Gaussians are fit to determine the histogram centroids; note that these centroids are within the mass region predicted (completely independently) by the axion domain wall theory.

Rapid rotation of a rubble pile can be expected to give rise to mass flows and surface deformations, delaying disruption and thus increasing the amount of time the asteroid remains close to disruption. The effects of rotational mass transport are exhibited clearly by, for example, the Alpha component of asteroid (66391) 1999 KW4, which has deformed or flowed into a top-like shape such that the accelerations on the equator cancel to within 1% [40, 41, 42], with a rotation period only 12% longer than the spherical RPL period for its density. Such mass movements will soften the RPL under YORP torquing, keeping bodies rotating near, but slightly below, their formal disruption limit, and delaying complete disruption[43, 44].

In the CCO hypothesis it is straightforward to take the observed radius and rotation frequency and estimate the mass of the CCO core, M$_Q$, with

$$M_Q = R_A^3\,(\frac{\Omega^2}{G} - \frac{4\pi\rho_A}{3}). \tag{2}$$

(This equation assumes a spherical body, an ordinary matter density of ρ_A and zero tensile strength.) Figure 3 shows a histogram of the number of CCO candidates as a function of the CCO mass inferred using Equation 2, both for all bodies with periods $<$ 2.2 hours, and for the VFR objects only, in both cases assuming ρ_A = 2300 kg m^3, together with the theoretically predicted mass range. It is striking that these mass ranges overlap: the very size range where CCO cores should dominate the mass of strange asteroids, and thus bind bodies gravitationally well beyond any ordinary matter RPL, is also the range where bodies are actually bound well beyond any ordinary matter RPL. Gaussians are fit to each histogram to estimate the center and spread of the distribution; the two data sets agree with well, with estimated centroid masses of 2.0 and 2.2 $\times$ 10^{10} kg, respectively, both towards the upper end but still within the range predicted by the axion domain wall model for CCO formation. If this is an indication of condensed matter core masses, and if the CCO hypothesis is correct, these data thus predict that the axion decay constant, f$_a$, should be found near the upper end of its predicted range (i.e., $\sim$ 2.8 $\times$ 10^{11} GeV).

Solar System CCOs as a Power Source

Oaknin and Zhitnitsky [4] hypothesized that CCOs could resolve the baryon asymmetry problem (the apparent predominance of normal matter versus antimatter in the universe) if the ratio of antimatter to matter CCOs was roughly 3:2. Such antimatter CCOs should survive to the present; CCOs would be protected from environmental interactions by their large superconducting gap energy, $\Delta \sim$ 100 MeV. Any incoming baryons would need to possess at least this much kinetic energy to break Cooper pairs and extract quarks from the superconductor [7]. A CCO would thus reflect any incident baryons with energies much less than Δ[4]; antimatter CCOs could thus potentially survive in the interiors of ordinary matter bodies, even at the center of the Sun, as even there thermal energies are much less than 100 MeV. It is not necessary, however, for there to be a substantial fraction of antimatter CCOs for CCOs to be used in the production of antimatter.

In common with BCS superconductivity, CFL superconductivity should support a form of Andreev reflection[7] for interactions with incident baryons with kinetic energy $> \Delta$, which would provide a means of CCO energy production. In Andreev reflection, quarks impacting on the CCO surface at or above the superconducting gap energ can pass inside the CCO, creating a new Cooper pair inside the superconductor through the creation of particle-antiparticle pairs, yielding one or more antiparticles leaving the CCO boundary (in other words, as seen from the outside, Andreev reflection consists of the reflection of an incoming particle as its antiparticle). It may thus be possible to create antimatter by radiating CCOs with 100 MeV particles, and it certainly should be possible to extract energy from a CCO by creating new Cooper pairs from 100 MeV particle streams, as these quarks will have a lower total energy after their insertion. Zhitnitsky [1, 2] describes an approximate theory for the growth of CCOs; the energy release from CCO particle insertion can be 10 % or more of the total mass energy inserted into the CCO, for a yield of potentially 10^9 kg or more of antimatter from each 10^{10} kg CCO. Strange asteroids would thus be a resource for the future, as their physically small ($\sim$ 1 mm radius) quark matter cores could be extracted by mining operations for subsequent exploitation, with a single 10^{10} kg CCO potentially producing $\sim 4 \times 10^{25}$ Joules worth of antimatter, sufficient (ignoring any losses) for $\sim$ 85,000 years worth of current human energy consumption [45], and also sufficient to accelerate a megaton mass spacecraft to close to the speed of light.

Conclusion

The CCO theory can be confronted with observations in the solar system in a number of ways (not the least by the independent determination of the density of VFR asteroids), and should be either ruled out or provisionally confirmed in the next few years. It seems clear that, if the existence of strange asteroids is confirmed, CCOs will be deeply involved in the powering of interstellar travel. This could be done either directly, by incorporating CCOs in the spacecraft propulsion (which, given the likely CCO mass range, would indicate starship masses in at least the megaton range), or through the production and storage of antimatter. In either case, CCOs should enable interstellar travel at a substantial fraction of the speed of light. CCOs would also have a profound impact on research in gravity and quantum theory (enabling, for example, “laboratory” tests of General Relativity and furthering experimental particle physics without requiring ever-larger colliders[46]), and of course as a terrestrial and general Solar System energy source. For all of these reasons, it seems very likely that, if CCOs are confirmed, they will be the subject of intensive spacecraft exploration, and that the future development of starships will depend on the results of that exploration.

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