Powering Starships with Compact Condensed Quark Matter

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(to appear in the *Proceedings of the 100 Year StarShip 2013 Symposium*)

November 7, 2013

Abstract

Compact Composite Objects (CCOs), nuggets of dense Color-Flavor-Locked Superconducting quark matter created before or during the Quantum ChromoDynamics phase transition in the early universe[1, 2, 3], could provide a natural explanation for both dark matter and the observed cosmological baryon asymmetry[4, 5, 6], without requiring modifications to fundamental physics. This hypothesis predicts a relic CCO population in the solar system, captured during its formation, and thus both massive strange matter cores in the centers of the Sun and planets, as well as a present-day population of "strange asteroids," bodies with mm-radii quark matter cores and ordinary matter (rock or ice) mantles. Methods based on neutrino radiography and solid-body mechanics are developed to detect such strange matter cores in solar system bodies. The CCO hypothesis is directly 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 the existence 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. Through a process analogous to Andreev reflection in superconductors[7], even normal matter CCOs could be used as antimatter factories, potentially potentially producing 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.

1 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.

Compact quark objects would represent a bound state of matter left over from epochs near the QCD phase transition, when the the density was $> 4 \times 10^{17}$ kg m^{-3} (the nuclear density). 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. CCO dark matter is thus a new variant of an old idea. 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]. CCOs made of CFL quark matter are thought to be stable at zero temperature, and could in fact be the fundamental state of matter, both more stable than ^{56}Fe and (if CCOs dominate the dark matter) more prevalent than ordinary hadronic matter.

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_Q, 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; the current experimental f_a limits[20] restrict the stable CCO mass range to

$$10^5\mathrm{kg} \lesssim M_Q \lesssim 4 \times 10^{10}\mathrm{kg}, \tag{1}$$

with the actual stable CCO mass range being a sub-range of less than two orders of magnitude in mass located within that range.

CCOs are consistent with the observational constraints on CDM not through new physics and weak interactions with ordinary matter, but through their macroscopic size, very small cross section to mass ratios and high binding energies. Figure 1 shows the most stringent current limits on the masses of compact condensed quark matter (see the Figure caption for more details). The lowest mass limits result from laboratory experiments, the highest mass limits are due to gravitational microlensing and cosmological constraints, while a range of intermediate masses is excluded by seismological constraints, effectively using the entire Earth and the Moon as a detector. Figure 1 shows that the stable mass range of Equation 1 is not excluded by any of these existing experimental constraints. Figure 1 also shows the inferred CCO mass range derived from asteroid observations, as discussed in Section 3.

2 CCOs 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), as interacting shock-waves cause density perturbations to exceed the

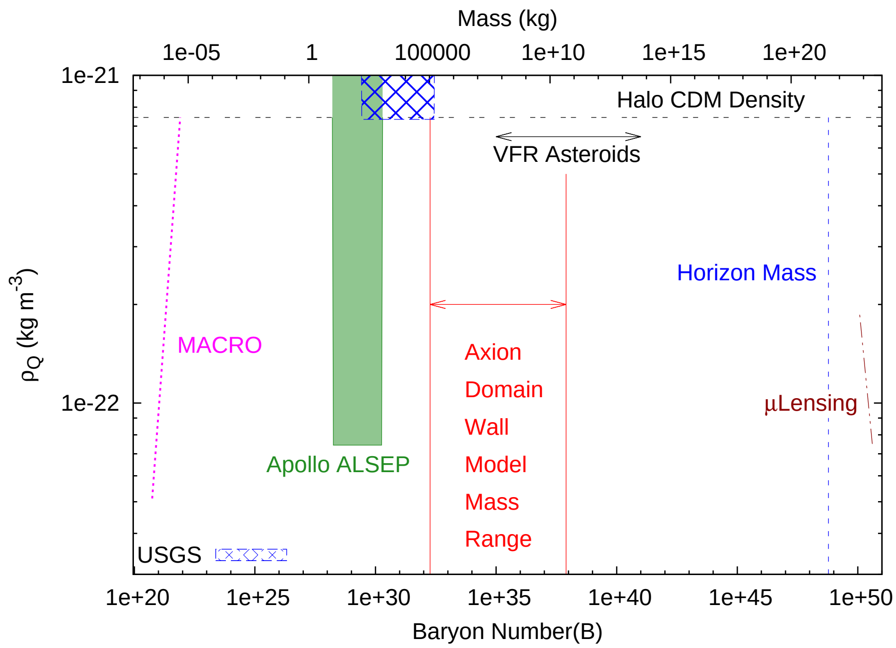

Figure 1: Limits on CCOs as a function of mass, assuming a monochromatic CCO mass spectrum. The experimental "asteroid constraints" and the theoretical "axion domain wall mass range" are included regions, which do not conflict with any of the other, experimentally excluded, mass ranges. The MACRO[21] 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].

local critical density[26]. The shocked gas then becomes gravitationally unstable and collapses, with stellar systems forming out of fragments of the collapsed material. Dark matter would not be directly perturbed by gas pressure changes during collapse but it would respond to the gravitational potential changes caused by these fluid motions and can become entrained in the collapsing cloud. In particular, a relatively 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 the resulting planetary systems, including during the formation of our solar system.

While this gravitational capture mechanism would apply to most dark matter candidates, many hypothesized forms of dark matter do not interact much with ordinary matter under any circumstances, and thus would have a negligible influence in the subsequent development of the planetary system. CCO dark matter, however, would actively influence subsequent events, leading to tests of the CCO hypothesis. CCO dark matter would, for example, possibly cause heating and radiation events in the early solar system through mergers and annihilation of quark matter condensates, which would leave detectable signatures in chondrules and other meteoritic material. CCOs at the upper end of the stable mass range could also be important in planetary formation, providing high mass-to-area-ratio planetesimal nucleation sites and thus resolving the "meter barrier" issue[27, 28, 29] in the growth of protoplanetesimals.

Quark matter in the solar system would, after taking part in planetary formation, mostly now reside at the center of the Sun, planets and smaller bodies, leading to at least two further tests of CCO dark matter, through the detection of quark matter cores in large bodies by neutrino radiography and through the detection of quark matter cores in small bodies through their solid-body dynamics. The first test will be briefly described in this section, while the second will be discussed in more detail in Section 3.

Given the relatively small mass of primordial CCO material likely to be captured in the solar system, massive bodies such as the Earth would have only a small fraction of their total mass in CCO cores. If it is assumed that the solar system formed in an Orion-sized molecular cloud with the same density of dark matter as at the Sun's present location in the Galaxy, then (ignoring any subsequent antimatter annihilation) about 3×10^{-5} of the mass of the solar system would be quark matter. If it is further assumed that the distribution of dark matter in the solar system mimics the present-day distribution of ordinary matter then $\sim 3 \times 10^{-5}$ of the mass of the Earth, or $\sim 2 \times 10^{20}$ kg, would be captured quark matter, which would presumably by now have all collected in the center of the planet, forming an $\sim$ 3.5 m radius strange matter sphere. Even though these interior quark matter cores would be physically small, they could actually be detected and studied with existing technology using neutrino radiography, as internal quark matter should be effectively opaque to neutrino beams generated by particle accelerators.

The absorption from the neutrino-nucleon (νN) optical depth [30] is given for an incident beam of energy E by

$$\frac{I}{I_0} = \exp - \frac{\sigma(E) D < \rho >}{M_N}, \tag{2}$$

where I / I_0 is the diminishment in luminosity, σ_E the cross sectional area at the beam energy, E, D the distance of propagation through the body, $< \rho >$ the mean density, and M_N the mass per nucleon. If for simplicity it is assumed that the cross section is the same for ordinary and strange matter, then the optical depth for a 7 m raypath through the CCO core (with $< \rho > \sim 10^{18}$ kg m^{-3}) would be $\sim 10^8$ times the optical depth for the 12,700 km antipodal raypath through the entire (ordinary matter) Earth (with $< \rho > \sim$ 5500 kg m^{-3}). This difference in optical depths makes radiography a natural tool for the detection of dark matter cores.

The CERN Neutrino beam to Gran Sasso (CNGS) project [31], which studied neutrino oscillations and propagation speeds using a 17 GeV neutrino beam sent over a 732 km baseline, shows the capabilities of current technology for neutrino radiography. Using the νN cross section for a beam of 10 GeV neutrinos of $\sim 10^{-41}$ m^2 [32], then I / I_0 transiting the Earth while avoiding any quark matter core would be $\sim$ 0.9996 while I / I_0 transiting through the center of the CCO core would be $\sim \exp^{-42,000}$, i.e., zero to a very good approximation. If a 10 GeV neutrino beam was generated by a terrestrial accelerator and aimed directly down at the center of the core the dense quark matter in a 3.5 m radius core would thus cast an $\sim$ 14 m diameter neutrino shadow at the accelerator's antipode, smaller than the 6.7 m x 6.7 m OPERA detectors. Although the length of an antipodal baseline would reduce the expected event rate by a factor of roughly 300 compared to CNGS baseline, the OPERA experiment resulted in 15223 detections [33]. An antipodal repeat of this experiment would thus be expected to result in $\sim$ 50 detections (outside of the core's shadow) or 0 detections (fully inside the shadow), which should be sufficient statistics to claim (or deny) the presence of such a core. By having multiple detectors, it would be possible to build up a true neutrino radiograph (projected image) of any quark matter at the center of the Earth.

While both logistical and technical considerations would probably result in an antipodal neutrino telescope being placed in deep water, instead of inside tunnels as for the CNGS, the current long baseline neutrino experiments undoubtedly show that the technology exists to confirm the existence of a CCO core inside the Earth by neutrino radiography. If the existence of a core can be confirmed, the same technology could be used to measure the size of the core and to study the physics of neutrino absorption and oscillation in strange matter, and possibly even to detect CCO core Slichter modes, if these should be sufficiently excited.

3 Observational Constraints on the Mass of Strange Asteroids

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 $\lesssim$ 200 meters, would, if they have a CCO core at all, be truly "strange" asteroids, as a large part of their total mass would be provided by their strange matter cores. This additional mass would greatly increase their bulk density, potentially to values $\gg$ the density of Osmium (the densest stable element, with ρ = 22587 kg m^{-3}). The most straightforward way to conclusively find strange asteroids would thus 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[34], and radiative torques by the Yarkovsky-OKeefe-Radzievskii-Paddack (YORP) effect[35]. Many small and medium sized asteroids are apparently spun up by YORP and rotate near or at their limit rotation[36], 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[37, 38, 36] between asteroid radii and rotation periods, using the complete set of rotation data available as of November, 2012[39, 40]. The asteroids can be usefully divided into three separate radius ranges with apparently different rotational regimes. Asteroids with radii $R_A > 50$ 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 $< R_A \leq$ 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[37]. Finally, "small" bodies with $R_A \leq 200$ m are 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 surface rotational disruption. For a spherical ordinary matter body (denoted by subscript "A") with uniform density ρ_A rotating at a frequency, Ω, mass loss would begin at the rotational RPL frequency, Ω_{RP}, with

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

Equation 3, together with the apparent RPL rotation limit of 2.2 hours, implies a bulk asteroid $\rho_A \sim 2300$ kg m^{-1}, which is within the uncertainty of the average density of

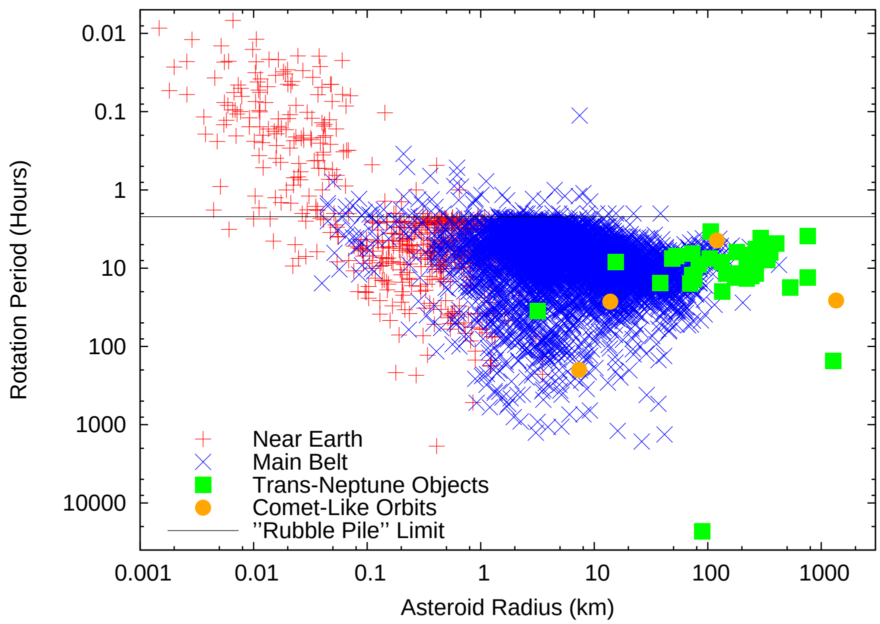

Figure 2: The asteroid rotation period-radius relation for all 5077 bodies with rotation and radius data, based on the November 2012 Asteroid Light Curve Database[39], after the removal of any flagged data. The Hungaria and Mars Crossing asteroids are included in the Main Belt asteroid category in this 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 3 is also shown.

the common S type (stony) asteroids [41]. Based on Equation 3 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.)

Rapid rotation of a rubble pile can be expected to give rise to mass flows and surface deformations, increasing the amount of time the asteroid can evade rotational disruption under radiative torquing. 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% [42, 43, 44], 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[45, 46].

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

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

(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 4, 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.

Figure 1 shows that the CCO mass range inferred from solar system asteroid data is consistent with both experimental constraints on CCOs and lies within the upper end of the mass range in Equation 1, suggesting the axion decay constant lies within the upper end of its current experimental constraints. It is striking that theoretically predicted and observationally inferred CCO mass ranges overlap: the very size range where CCO cores are predicted to dominate the mass of strange asteroids, and thus bind bodies gravitationally beyond the 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 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).

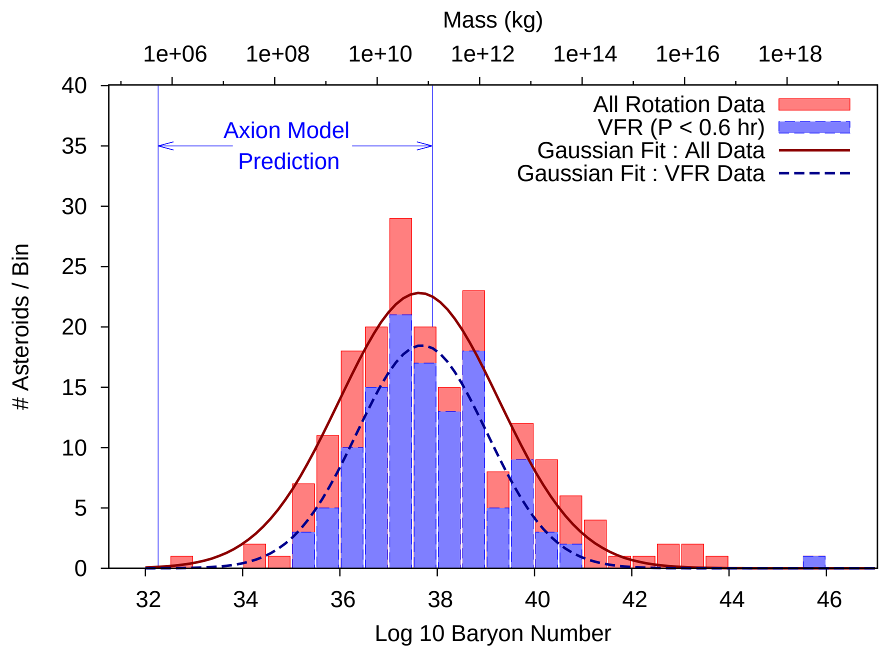

Figure 3: The number of candidate strange asteroids as a function of the CCO core mass required to prevent rotational disruption, assuming gravitational binding only. Estimates are provided from asteroid rotation data referenced to a rubble pile model with a default ρ = 2300 kg m^{-3} for all of the 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.

4 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; both matter and antimatter 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.

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, which was first demonstrated in BCS superconductivity, particles impacting on the CCO surface at or above the superconducting gap energy can pass inside the CCO, creating new Cooper pairs inside the superconductor through the creation of particle-antiparticle pairs, yielding one or more antiparticles leaving the CCO boundary (in other words, seen from the outside Andreev reflection consists of the conversion of an incoming particle into 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 (~ 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 [47], and also sufficient to accelerate a megaton mass spacecraft to close to the speed of light.

5 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 within a relatively short period of time. 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 the many megaton mass range), or through the production and storage of antimatter. In either case, CCOs could 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[48]), and of course as a general terrestrial and 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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