

Compact Ultradense Matter Impactors

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We study interactions of meteorlike compact ultradense objects (CUDO), having nuclear or greater density, with Earth and other rocky bodies in the Solar System as a possible source of information about novel forms of matter. We study the energy loss in CUDO puncture of the body and discuss differences between regular matter and CUDO impacts.

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Introduction.—What if there are “dark” matter meteor and asteroidlike bodies in the Universe? Could some of them have collided with Solar System bodies and Earth? On account of a high density resulting in a small geometric cross section and a high surface gravity, such compact ultradense objects (CUDOs) “dressed” or not by normal matter are likely to survive transit through Earth’s atmosphere. CUDOs’ high density of gravitating matter provides the distinct observable difference in the outcome of their collisions with rocky bodies, the surface-penetrating puncture: the CUDO will practically always enter the target body, and many will exit the body, with only a fraction of the kinetic energy damaging the solid surface. We therefore refer to CUDO collisions with Solar System rocky bodies as “punctures.”

We describe here the physics of CUDO puncture focusing on Earth, and extend the considerations as applicable to Mars, the Moon, and other solar rocky bodies. Simple features are discussed which distinguish their appearance from normal matter meteorite impacts. This should provide a path to recognizing the presence of asteroid CUDOs in the Universe, and as such offer new insights about novel forms of ultrahigh density matter, such as strangeness-rich nuclear matter [1,2]. Light nuclearite strangelets have not been found in soil from the Moon [3], nor in laboratory production experiments [4], but the space search continues with ongoing efforts to observe the strangelet flux with the AMS-spectrometer mounted on the International Space Station [5].

This work extends the mass range of prior puncture studies. (a) By strange quark matter “nuclearites” [6] of $M \lesssim 10^4 m_{\text{proton}}$ were recognized as passing across a rocky body on account of their tiny size and subatomic self-binding, and capable of generating seismic disturbances [6,7]; such seismic signatures have been searched for on Earth [8] and the Moon [9]. (b) Similar consideration was also made for micro-sized black holes [10]; that work was considerably extended recently [11,12].

The CUDO mass range that is not excluded by experiment is rather wide. An upper mass limit for massive “invisible” objects is provided by microlensing

surveys: massive compact halo objects with $M \gtrsim M_{\oplus} = 5.97 \times 10^{24}$ kg (i.e., larger than Earth’s mass) are ruled out [13,14]. Massive compact halo objects comprise two object classes: (i) normal density objects such as planets and dwarf stars, and (ii) neutron matter and higher density objects which we study here. The lower mass limit originates in gravitational stability such as would arise from a relatively loose conglomerate of otherwise noninteracting heavy dark matter particles.

We begin considering the potential sources of CUDO and the flux and puncture frequency by massive CUDOs. We then turn to a discussion of energy deposition on puncture. We close with a short discussion of the event signatures.

Potential sources of CUDOs and CUDO rate of collisions.—CUDO nuclearite meteors can be produced as fragments from a collision of neutron star cores that contain strange quark matter (nearly $s = u = d$ -quark abundance symmetric matter) [15,16]. Such macroscopic nuggets of strange quark matter may be sufficiently bound to be stable on a cosmological time scale [17]. However, the expected flux of nuclearite CUDOs created in stellar evolution events is naturally small and their rocky body impacts would be very rare.

Even if the flux of massive CUDOs such as nuclearite strangelets decreases with their mass like $1/M$ [6,18], consideration of the integrated flux over a period of billions of years will result in the accumulated number of heavy puncture events being much more numerous than the expected short observation period acoustic signal events of light CUDOs.

During this long puncture “observation” time the Solar System samples a large domain of the Milky Way, circling the galactic center a few times and, in particular, it passes through spiral arm regions comprising higher density of visible matter. It is likely that CUDO abundance of any type is enhanced in high visible matter density domains of the galaxy, resulting in periodic enhancement of CUDO flux within the solar system as compared to the present condition.

Study of the Bullet Cluster [19] demonstrates dark matter as an independent, dynamical, and gravitating component. There is no direct or indirect observational evidence

constraining the state in which dark matter is to be found. The estimated dark matter density in the local area of the Milky Way is $\rho_d = 5.3 \times 10^{-22} \text{ kg/m}^3$, roughly equal to the averaged local density of visible matter [20]. Overall, by mass, the dark matter is about 4 times as abundant as is visible matter.

Considering that dark matter is the dominant form of matter in our time, recent (on the scale of 100 millions of years) impacts of dark matter CUDOs should be frequent: The Sun and the large Solar System bodies comprise a vastly dominant fraction of the visible matter comoving with Earth in the galaxy. Since by mass the abundance of visible and dark matter is similar, it follows that even if a relatively small fraction, e.g., 10^{-6} of dark matter is bound in meteor-sized objects, their flux would be similar to the number of normal matter meteorites, though the distribution in space could be very different.

The above argument presumes that a tiny fraction of all dark matter is clumped. Clumping of the very heavy “cold” dark matter dust has so far received little attention and a study of this process is beyond the scope of this work. However, large scale visible matter structure in the Universe depends on the existence of gravitating dark matter density fluctuations formed in the early Universe. Therefore, the question is not if dark matter fluctuations exist but if yet higher density gravitationally bound dark matter objects can arise.

Beyond the first step described above there could be a continued mutual speed-up and reinforcement of visible matter and dark evolutionary dynamics: once enough visible matter converged together near the first dark matter fluctuations, and first stars form, these stars become themselves gravitational attractors helping to aggregate dark matter, assisting in the formation of dark, gravitationally self bound objects, which can be freed at the end of some stellar evolution cycles. The lighter CUDOs with a mass significantly below that of the Earth are those that would be of interest in the puncture process we address here.

Like in the study of neutron stars, dark matter CUDO properties are obtained solving Oppenheimer-Volkov equations for a heavy gravitating dust [21,22]. The higher the mass of the cold dark particles, the smaller the Oppenheimer-Volkov upper mass stability limit, and the fewer particles that are needed to form a self-bound body. Should the upper stability mass limit be exceeded, a dark black hole is formed in a gravitational collapse [12]. Aside from this upper mass limit there is a minimum mass required for the presence of sufficiently high self gravity to provide stability in during the Universe’s evolution to the current epoch.

We consider punctures by a member of the cloud of objects comoving with the solar system. Any such accompanying CUDOs have isotropic velocities $v_{\text{gal}} \sim$ a few km/s relative to the solar system. Given that the two classes of collisions (normal and CUDO) with rocky bodies were not distinguished before, we consider the

velocity distribution of CUDOs to be similar to that of nonsolar system visible matter impactors. We note a potential third class, a fast CUDO impactor: should CUDOs constitute a fraction of the primordial dark matter, they should form an independently rotating galactic halo, resulting in a much higher relative velocities $v_{\text{halo}} \sim 200 \text{ km/s}$. Seeing the inverse dependence on v in the equations below, such impacts will be yet less damaging to the target body, but entail a much greater local force.

A conservative CUDO puncture rate is obtained by ignoring the concentration of CUDOs in the proximity of the Solar System, i.e., spreading CUDO matter, taken as equal to the solar system visible matter, over the volume cell in the Milky Way occupied by the solar system. For comoving CUDOs the gravity of the Sun focuses objects passing nearby, increasing the flux of objects whose trajectories enter the inner solar system (achieving a minimum radius smaller than Earth’s orbit $R_{\text{orbit,E}}$) and enhancing in that way the effective cross section

$$\sigma = \left(1 + \frac{2GM_{\odot}}{v_{\text{gal}}^2 R_{\text{orbit,E}}} \right) 4\pi R_{\oplus}^2. \quad (1)$$

($4\pi R_{\oplus}^2$ is the planetary detector surface area).

We do not know the CUDO mass distribution in the flux. Hence, what follows is for an average mass compact impactor. The CUDO number density $n = \rho_d/M$, leads to an expected annual event rate for puncture on the Earth,

$$N_{\oplus}(v, M) = n\sigma v \simeq 3 \times 10^{-18} \frac{\text{km/s}}{v} \frac{M_{\oplus}}{M} \text{ yr}^{-1}, \quad (2)$$

where M is the mass of a typical CUDO and v is the velocity attained by the object at $R_{\text{orbit,E}}$. We expect up to a dozen collisions with CUDOs of $M < 10^{-9} M_{\oplus}$ over the course of Earth’s history. If the CUDO mass spectrum parallels the normal matter impactor mass spectrum [23], lower mass punctures will be significantly more frequent and collisions with $M < 10^{-15} M_{\oplus}$ (i.e., objects of mass below 6 million tons) occurring as often as every few hundred years.

CUDO punctures.—A CUDO comoving at low relative velocity outside the solar system achieves $v \sim 20\text{--}60 \text{ km/s}$ relative to Earth. As a result, the CUDO penetrating the crust will be supersonic in the mantle ($c_s \sim 8 \text{ km/s}$). Understanding the dynamics of a supersonic compact gravitating body passing through a dense planetary medium is the key physics challenge. We generalize and expand on preceding considerations of punctures by micro black holes [10,11].

We propose estimates of magnitudes based on linear response and two mechanisms of energy exchange with planetary matter: (i) pulverization and entrainment of rock nearest the trajectory of the object, and (ii) creation of a supersonic shock. We expect the assumption of linear response breaks down for masses greater than some $M_s(v)$, resulting in a more inelastic nonlinear response. The following scaling considerations can be considered valid only

for $M < M_s$ and further exploration of $M_s(v) < 10^{-2}M_\oplus$ is left to future considerations.

Entrainment of material.—In order to carry material away, the CUDO tidal force must break it into pieces small enough to be gravitationally captured. When the differential (tidal) acceleration over a length L exceeds the capability of the material to change density elastically, the integrity of the material is compromised, we expect a fracture to open within the length L . We compare the differential gravitational pressure, which is the product of the tidal acceleration and mass per unit area,

$$P(r - L/2) - P(r + L/2) = \frac{2GML}{r^3} \rho L, \quad (3)$$

to the material's bulk modulus $K = \rho c_s^2$, which is a function of the density ρ and the sound speed c_s . L then scales with the distance r from the trajectory as

$$\frac{L}{R_c} = A_f \left(\frac{r}{R_c} \right)^{3/2}, \quad (4)$$

with $A_f = \sqrt{2}(c_s/v)$. R_c is the capture radius [24]

$$R_c := \frac{4GM}{v^2} = 10^6 \left(\frac{40 \text{ km/s}}{v} \right)^2 \frac{M}{M_\oplus} \text{ m} \quad (5)$$

within which material can be entrained with the object and acquires its velocity v . Figure 1 shows that $L/R_c < 0.1$ for radii less than R_c . All capture-eligible material is broken into pieces small enough to be pulled along with the object, thus forming a slug of fine particulate matter carried with the CUDO even as it exits the target body.

The velocity of the CUDO is reduced by the capture of material, because the slug of entrained material must acquire the comoving kinetic energy, the average gain in potential gravitational energy being small in comparison.

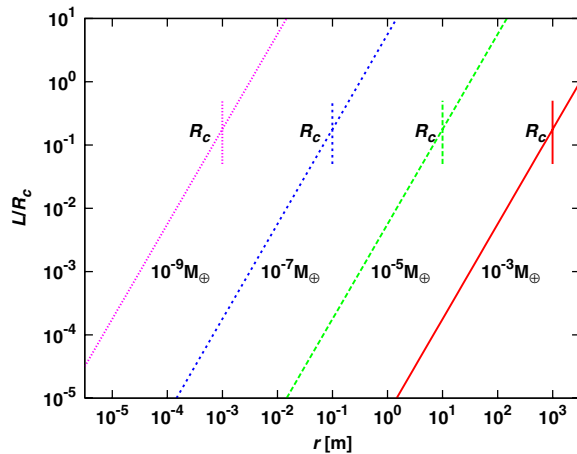


FIG. 1 (color online). The tidal fracture length scale L from Eq. (4) normalized to the capture radius R_c Eq. (5) as a function of distance from the trajectory. The velocity of the compact object is fixed at $v = 40 \text{ km/s}$ and $c_s = 8 \text{ km/s}$ used for the speed of sound in the mantle; a higher v only reduces L/R_c .

$$\Delta E = A_k \rho R_\oplus \pi R_c^2 \frac{v^2}{2} \approx 6.4 \times 10^{31} \left(\frac{40 \text{ km/s}}{v} \right)^2 \left(\frac{M}{M_\oplus} \right)^2 \text{ J}. \quad (6)$$

A_k contains factors for capture efficiency (which may differ from unity due to drag between captured and neighboring material) and impact parameter b (which determines total volume of tube radius R_c around the trajectory). In an ideal fluid model, capture efficiency is 100% and $A_k = 2\sqrt{1 - b^2/R_\oplus^2}$. The numerical coefficient is obtained with the density of mantle $\rho \approx 4000 \text{ kg/m}^2$ and considering $A_k = 1$. However, there is also the kinetic energy and the drag of uncaptured material which we expect to be of similar magnitude.

Comparison to the kinetic energy before collision,

$$\frac{\Delta E}{E} = A_k \frac{\rho}{M} R_\oplus \pi R_c^2 \approx 0.013 \left(\frac{40 \text{ km/s}}{v} \right)^4 \frac{M}{M_\oplus}, \quad (7)$$

suggests that objects $M < 10^{-4}M_\oplus$ pass completely through Earth without being stopped and the energy transferred to the entrained matter is at and below 1/1000. While the total energy deposited in the target body is a small fraction of the total kinetic energy, the energy deposited by the CUDO at the surface is still much smaller. A normal matter meteorite is stopped soon after impacting the surface, which requires that it dissipates all of its kinetic energy in a relatively small target area. Therefore, the CUDO puncture is much less destructive than a normal matter meteorite.

We note features specific to the case of strangelet CUDOs which originate in the electrical charge of the strange quark matter core. Strangelet CUDOs are expected to acquire a dressing of normal matter, forming a ‘‘crust’’ [25]. For the mass range of interest, the kinetic energy will suffice to press additional matter across the electric potential into the quark matter core. Consequently, additional matter can be captured. The resulting change in strangelet mass will depend primarily on the amount of matter encountered during the puncture: we find the fractional mass change corresponding to Eq. (7) is of order $10^{-3}(M/M_\oplus)$, and only 150 times larger when considering the Sun as a target. However, a charged strangelet CUDO [26] would lose additional energy during the puncture due to electrical ionization and polarization effects, which may be particularly important in strangelet collisions with the Sun. Solar impacts as well as strangelet-strangelet collisions depend further on strange quark matter bulk properties. These are the subject of present day interest in view of nontrivial color-superconducting and color-flavor locked cold quark matter phases [27].

To establish that material in and around the slug is indeed molten, we look at temperature in the bow shock

$$k_B T = A_T v^2 \quad (8)$$

with A_T depending on the atomic composition of the material. Taking an ideal gas model [28] in view of the

high temperatures expected gives $A_T = 3 \times 10^{-27}$ kg and $T \approx 10^5$ K. Estimating based on the continental secular cooling rate of Earth ~ 80 mW/m², the conduit formed by the puncture could remain a significant local source of thermal energy, recognized by transient deep-origin volcanism not related to plate boundaries.

Supersonic shock wave.—At ranges larger than R_c tidal stresses generate an intense seismic wave. Since the velocity of the CUDO is greater than the speed of sound in the mantle or crust, the wave is compressed into a shock. Energy deposition via coherent acoustic emission has been given as [Eq. (13) in Ref. [11]]

$$\left. \frac{dE}{dx} \right|_{\text{shock}} = A_s \pi R_c^2 \rho v^2 \approx 1.9 \times 10^{26} \left(\frac{M}{M_\oplus} \right)^2 \left(\frac{40 \text{ km/s}}{v} \right)^2 \frac{\text{J}}{\text{m}}, \quad (9)$$

where $A_s = (1/8) \ln(c_s^2/4\pi G \rho a^2)$, a being typical inter atomic spacing. This estimate finds a large amount energy in the compression wave, 40 times the captured matter kinetic energy Eq. (6).

CUDO stability on impact.—Micro black holes are stable and puncture through the target. Nuclearite CUDOs are bound by nuclear scale forces and if stable on cosmological time scale, atomic scale forces cannot pull them apart. On account of the much larger dark matter particle mass, the dark matter CUDO has a very high density, and its Roche limit ($2\rho_t < \rho_c$ for CUDO at target surface) is not relevant in stability consideration. In fact our evaluation of the effect of a CUDO on the target body is like an “inverse” Roche process in that the target structure is locally broken by the tidal forces of the high density CUDO.

Conversely, for a gravitationally self-bound CUDO of sufficiently small mass, the potential energy at the surface will be small enough to allow the target induced polarization force to shear and attract particles from the CUDO. The qualitative condition for transfer of matter is that the presence of the target body opens a potential valley from the binding potential of the CUDO at its surface R_c towards the potential of the target body t . The minimal stable mass condition arises from the requirement that transfer of CUDO particles to target begins after surface penetration,

$$M_c > M_t \frac{R_c}{R_t}. \quad (10)$$

We find a large domain between this lower, and the upper gravitational collapse limit, wherein one can consider CUDO collisions with Earth and other rocky bodies [29].

CUDOs in particle physics.—The features of CUDO impacts discussed here arise from their compactness, and the mass-radius scale, for beyond-standard-model (BSM) CUDOs set by the energy-mass scale of the dark matter particles [21,22]. Strangelet CUDOs and BSM CUDOs are distinguished by the large splitting between their respective energy scales, ~ 1 GeV and ≥ 250 GeV. Terrestrial

impacts should allow differentiation on the corresponding scale of impacting CUDOs mass and size. Considering the upper and lower mass limits originating in the constituent particle properties [29], a constraint on the dark matter energy-mass scale could arise. We expect to at least be able to differentiate heavy BSM particle CUDO from, e.g., color-flavor-locked quark matter [27,30]. Such quark matter CUDO impacts are believed to have several distinctive features [31].

Another aspect controlled by the BSM-dark matter energy scale is CUDO formation scenario. Compact, and relatively small in particle number CUDOs could be formed primordially by density fluctuations [32], potentially absorbing a large fraction of dark matter particles as used in flux estimate Eq. (2). Strangelet CUDOs can be formed in more recent times, e.g., in collapsing stars [16].

Discussion and outlook.—The salient observable feature of CUDOs is their capability to create puncture in rocky bodies. On account of the relatively small energy loss distributed across the puncture conduit, even relatively massive CUDO punctures preserve the integrity of the target and inflict in such event a relatively small shotlike damage.

While the exit “wounds” must be fewer than puncture entries, on account of possible CUDO instability after entry, their appearance should be more characteristic considering that there is little else in the Universe that can generate an exit conduit from a body and, considering Earth puncture, can transport material into the upper atmosphere. A puncture event may be thus recognized by coincidental presence of impact and ultrastrong “volcanic” eruption. The AD 536 event [33–35] which has lead to a major historical climate excursion invites reexamination as a possible full CUDO puncture, i.e., impact and exit accompanied by material transport into the upper atmosphere.

Most recent and present epoch CUDOs are possibly dressed in normal matter and thus many punctures are also “normal” meteorite impacts. Depending on the ratio of normal to CUDO mass and the composition of normal matter component, there are characteristic CUDO features in comparison to impacts by solely normal meteors: (a) Preceding the impact, in transit through atmosphere, the CUDO core binds and stabilizes even the heated meteorite material, making the normal matter impactor appear exceptionally stable. (b) At impact on the surface, the normal matter material will largely evaporate, if not entrained with the CUDO into the mantle and beyond. A possible signature of CUDO surface impacts is then the absence of both CUDO and normal impactor material. (c) At exit, the kinetic energy of the moving CUDO may create an exit “hump” and/or appearance of lava flow in environments where none should be present. While rapid terrestrial surface evolution would mask some exit features, they should be well preserved on Mars, the Moon, and other rocky bodies.

Present day models of meteor impacts do not introduce the possibility of a high density impactor and the resulting surface puncture. It is the absence of the CUDO type option in detailed impactor models that in our opinion leads to ongoing intense discussions within diverse geological and planetary communities regarding the priority of impacts versus eruptions, raising further questions about the mechanism of major unexplained phenomena (e.g., “Volcanism, impact and mass extinctions: incredible or credible coincidences?” [36]). These topics are well beyond the current context, yet the wide ranging debates are indicating the need for a novel event type, and puncture seems to fit the need.

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