Could 1I/'Oumuamua be macroscopic dark matter?

David Cyncynates³, Emanuela Dimastrogiovanni¹², Saurabh Kumar¹, Jagjit Sidhu¹, and Glenn D. Starkman¹
¹CERCA/ISO/Department of Physics, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106
²Perimeter Institute for Theoretical Physics, 31 Caroline St. N., Waterloo, ON, N2L 2Y5, Canada and
³Stanford University, Stanford, California 94305, USA

1I/'Oumuamua, formerly known as A/2017 U1, is a sizable body currently passing through the solar system. It is generally considered to be a rocky asteroid-like object that came from another planetary system in the Milky Way. We point out that 1I/'Oumuamua may instead be a chunk of dark matter, a “macro,” possibly as massive as \(10^{25} g\) if it is of nuclear density. If so, then its passage will have caused measurable deviations in the orbits of Mercury, the Earth, and Moon.

On October 19, 2017, an “unusual object” was observed to be passing through the solar system. Temporarily designated A/2017 U1 and now renamed 1I/'Oumuamua by the Minor Planet Center (MPC) in Cambridge, Massachusetts, it was discovered by R. Weryk using the Pan-STARRS 1 telescope, and subsequently identified by him in the archived images of Oct 18. 1I/'Oumuamua appeared to come from within 6° of the solar apex – the direction that the Sun is moving (at about 20 km/s) through the solar neighborhood – with a hyperbolic excess velocity of approximately 26 km/s with respect to the Sun. This direction is almost directly “above” the ecliptic, so 1I/'Oumuamua did not have any close encounters with a solar-system planet before reaching perihelion inside Mercury’s orbit on Sept. 9, slingshotting under the Sun, and passing within about 24 million km of the Earth on its way back out of the Solar system.

K. Meech [2] “reported that in a very deep stacked image, obtained with the VLT, this object appears completely stellar.” In other words, 1I/'Oumuamua was too small to be resolved. It appears to have a featureless red spectrum. B. Gray calculated [1] that 1I/'Oumuamua would have a diameter of about 160 meters if it were a rock with a surface reflectivity of 10%. Explanations for 1I/'Oumuamua have focused on the possibility that it is an interstellar asteroid ejected from an extrasolar planetary system [3].

An alternative is that 1I/'Oumuamua is not any ordinary rock, but a macroscopic chunk of dark matter, a “macro” [4]. Contrary to widely held misconceptions, dark matter need not be in the form of weakly interacting elementary particles, but might instead be found in much larger pieces with masses best measured in grams or kilograms, and cross-sections best measured in cm². Specific candidates include primordial black holes [5,6], strange quark or baryonic matter [7,9], and other speculative approximately nuclear-density Standard-Model or Beyond-the-Standard-Model objects (nuclearites [10], quark nuggets [11,12], CUDOS [13], etc.).

Given that 1I/'Oumuamua was seen to reflect sunlight, we can eliminate the possibility that it is a primordial black hole. Strange baryonic matter, however, will reflect light, though no ab initio calculation of its reflectivity or spectrum would be reliable. Extending the calculations of Gray [1], we can conclude that if 1I/'Oumuamua is spherical it has a cross-sectional area

\[
\sigma_X \geq \sigma_X^{\text{min}} = 2 \times 10^7 \text{cm}^2.
\]

From figure 1 we see that macros with \(\sigma_X\) respecting (1) are allowed, even at 100% of the dark matter density for

\[
3 \times 10^{13} g \lesssim M_X \lesssim 10^{17} g \quad \& \quad 2 \times 10^{20} g \lesssim 2 \times 10^{24} g.
\]

This does not quite extend to objects of nuclear density, which would have \(M_X \gtrsim 2 \times 10^{25} g = 10^{-8} M_\odot\). However, a distribution of masses that included this is allowed [14].

We can estimate, how often one would expect a macro in this mass range to enter the inner solar system. Given a local density of dark matter of \(\rho_{DM} \simeq 7 \times 10^{-25} g/cm^3\), and a relative velocity for dark matter of \(\sim 250 \text{ km/s, and}\)
taking the “target” to be the inner astronomical unit, we find the rate to be

$$\Gamma \simeq 4 \times 10^{-7} \frac{10^{25} \text{ g}}{M_X} \text{ yr}^{-1}.$$  

(3)

We see that if 1I/’Oumuamua is a macro of nuclear density (the high end of the mass range), then its appearance, within about a decade of us being able to see it with a telescope like Pan-STARRS, would be quite fortuitous. The precise interpretation of this rate however is complicated by the fact that although 1I/’Oumuamua was on a hyperbolic orbit, it was moving approximately ten times more slowly than would be expected for generic halo-dark-matter. For an isothermal halo, only a small fraction of the halo dark matter would be expected to move this slowly.

On the other hand, an object of this size but mass $10^{13}$ g (the minimum allowed per figure [1]) would be expected to enter the inner solar system several times per hour. This suggests that we could rule out such objects as the dark matter by their non-observation.

If 1I/’Oumuamua is indeed dense macroscopic dark matter, then we would expect that its passage close to Mercury, the Earth and Moon would have measurable gravitational effects on their orbits. Simple estimates suggest that a passing macro would cause a displacement of approximately

$$\Delta x \sim \frac{G N M_X}{v^2} \simeq 300 \text{ m} \left( \frac{M_X}{10^{25} \text{ g}} \right) \left( \frac{50 \text{ km/s}}{v} \right)^2$$

in a body’s orbit, while altering its velocity by

$$\Delta v \sim \frac{G N M_X}{r v} \simeq 1.4 \times 10^{-3} \text{ m/s} \left( \frac{M_X}{10^{25} \text{ g}} \right) \left( \frac{10^7 \text{ km}}{r} \right) \left( \frac{50 \text{ km/s}}{v} \right).$$

Such displacements should be detectable. Preliminary estimates of the effects on orbital semi-major axes suggest that these are several times larger. Meanwhile, the tidal force on the extremely well measured Earth-Moon system should displace them relative to one another by an amount smaller than $\Delta x$ by a factor of approximately the lunar orbital radius divided by the distance of closest approach of the macro. This works out to a very detectable $\Delta x_{\text{Tidal}} \simeq 10$ m. In an upcoming work we will compare the observed motion of Mercury, the Earth, the Moon and 1I/’Oumuamua to their predicted paths, in an attempt to measure or place an upper limit on the mass of 1I/’Oumuamua.

The search for high density macros, such as primordial black holes or lumps of strange baryonic matter, must continue, even if one may have just crossed our paths. Perhaps in the future we will see a macro soon enough to rendezvous and measure its size and mass, detect the seismic signal of a macro’s lunar or terrestrial impact [10, 15, 19] or pick up the gravitational wave signal [17] of macros spiraling into the Milky Way’s central black hole.

Acknowledgments We thank David Jacobs, Bryan Lynn and Kellen McGee for influential and ongoing conversations on the detectability and fundamental physics of macros. SK, JS and GDS are supported by a Department of Energy grant DE-SC0009946 to GDS. ED was supported in part by Perimeter Institute for Theoretical Physics. Research at Perimeter Institute is supported by the Government of Canada through Industry Canada and by the Province of Ontario through the Ministry of Economic Development and Innovation.