The Color Out of Space

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In response to “Interstellar Overdrive” (Vol. 6, No. 3).

To the editors:

Since the early nineteenth century, astronomers have hypothesized the existence of interstellar comets. William Herschel obtained careful observations of two different comets, which he outlined in two papers published in 1812: “Observations of a Comet, with Remarks on the Construction of Its Different Parts” and “Observations of a Second Comet, with Remarks on Its Construction.”[1] Herschel discovered that the two comets attained different levels of brightness despite similar distances to the sun. This led him to speculate that some comets may originate beyond the solar system, and that the differences in their level of activity can be attributed to the accumulation of matter as they voyage through interstellar space:

> Should the idea of age be rejected, we may indeed have recourse to another supposition, namely, that the present comet, since the time of some former perihelion passage, may have acquired an additional quantity (if I may so call it) of *unperihelioned* matter, by moving in a parabolical direction through the immensity of space, and passing through extensive strata of nebulosity.[2]

This hypothesis was subsequently validated by Pierre-Simon de Laplace in his foundational work *Sur les cométes*. In *Essai philosophique sur les probabilités*, he even provided a surprisingly accurate calculation for the arrival rates of interstellar comets.[3] As part of Herschel and Laplace’s vibrant and imaginative construction of the cosmos, interstellar space was filled with freely streaming comets. These interstellar vagabonds would peacefully pass through the enormity of space until encountering a star like the sun, where they would erupt with violent cometary tails. In Herschel and Laplace’s cosmology, these comets should regularly appear in the night sky on unbound and hyperbolic trajectories.

The twentieth century brought significant advances in our understanding of comets that originate in the solar system. We now know that typical solar system comets arrive not from interstellar space, but from the Kuiper belt and the Oort cloud. Yet astronomers had been expecting to find interstellar comets since the days of Herschel and Laplace. The composition of the comet C/2016 R2, for example, is so anomalous that scientists have proposed that it has an interstellar origin.[4] Astronomers have even estimated the number of interstellar comets they would detect with future surveys based on the non-detections of any such objects.[5]

It was not surprising, then, when the first interstellar object was detected from the summit of Haleakalā, rushing through the inner solar system on the night of October 19, 2017. Within days, it had a name—‘Oumuamua—which roughly translates from Hawaiian as “a messenger from the distant past.” And in every way that astronomers expected the first interstellar comet to behave, ‘Oumuamua acted the opposite.

‘Oumuamua brought many mysteries, including a reddish color,[6] an elongated shape,[7] a non-gravitational acceleration,[8] and a lack of any detectable coma. Even its slow incoming trajectory implied a surprisingly young age,[9] less than about 40 million years.[10] This is much younger than might be expected for a typical interstellar comet ejected from a stellar system.

Grappling with our apparent isolation in the universe is an innately human experience. It is only natural then, to realize our collective isolation as a species, and to project onto the physical world a selfish communal desire to be discovered. Astrophysical advances, in turn, have provided a grander stage for the anthropomorphism of the natural world. It is not surprising that our first interstellar visitor, so tantalizingly reminiscent of Arthur C. Clarke’s *Rendezvous with Rama*, generated worldwide interest, along with claims of a non-natural provenance.

Science should be inherently unbiased and objective, although it rarely is. Just as we should avoid anthropomorphizing undeniably natural phenomena within the universe, we should also avoid being close-minded to the point we deny apparent exotism. The fact that ‘Oumuamua defied every expectation implies that the scientific community should *consider* every exotic hypothesis for its provenance.

The explanations for ‘Oumuamua can broadly be organized into two categories based on the proposed source of its anomalous acceleration. The first category relies on the assertion that the nongravitational acceleration was powered by solar radiation pressure. This idea was proposed by Marco Micheli et al. and was originally ruled out due to the assumed physical characteristics of the object in this scenario.[11] In order for solar photons to change ‘Oumuamua’s trajectory, it would need to be either extremely porous or very thin. This theory was reinvigorated by a series of investigations suggesting that ‘Oumuamua was the result of large-scale diffusion-limited aggregation—the equivalent of a kilometer-scale dust bunny or snowflake.[12] While this would explain the anomalous acceleration and lack of coma, it did not explain the object’s extreme geometry and young age.

Alternatively, if ‘Oumuamua was a millimeter thin membrane, radiation pressure could power the acceleration.[13] Contrary to what is stated in this review, the spin state of an elongated object under the action of radiation pressure is steady.[14] Moreover, this theory naturally explains the age, shape, and acceleration of ‘Oumuamua. The mere existence of such a radiation-powered thin membrane would imply intelligent design. But if the detection of ‘Oumuamua was coincidental, then the galaxy contains more than an Avogadro’s number worth of similar objects. The sheer implied number density is difficult to reconcile with an artificial origin.

The remaining theories rely on the sublimation of ice as the source of the acceleration.[15] From energetic constraints, the only viable accelerants are hydrogen, nitrogen, and carbon monoxide.[16] If ‘Oumuamua was a hydrogen iceberg that formed in a starless core in the interstellar medium, there would be a natural explanation for its acceleration, shape, young age, and the implied number density.[17] But the frigid temperatures required for the freezeout of solid hydrogen are close to that of the ambient cosmic microwave background and are difficult to justify theoretically.[18]

Solid nitrogen is an appealing candidate for the accelerant because astronomers have observed it on bodies in the solar system.[19] The problem with this explanation is that the implied galactic mass budget of these objects is difficult to harmonize with the formation mechanism.[20] Carbon monoxide is a similarly intriguing potential accelerant,[21] because it would imply an initial similarity with the second interstellar comet, 2I/Borisov, observed on December 8, 2019, and the comets native to the solar system. But given the non-detection of carbon monoxide with the Spitzer Space Telescope,[22] this hypothesis requires that ‘Oumuamua underwent variable levels of outgassing. While viable, this explanation is somewhat ad hoc.

There exists no explanation for the provenance of ‘Oumuamua that describes every mysterious property without theoretical or observational barriers. But there is reason for optimism because we *will* have answers, and very soon. The forthcoming Rubin Observatory Legacy Survey of Space and Time (LSST) will provide almost nightly coverage of the entire southern sky from the Atacama Desert and should detect about five interstellar objects like ‘Oumuamua every year.[23]

If the LSST had been online before ‘Oumuamua was discovered, performing an in situ interception mission would have been achievable and well within the capabilities of today’s rocket inventory.[24] Among all the interstellar objects that the LSST will detect, about one in five should be reachable targets for an interception.[25] With missions like the European Space Agency’s Comet Interceptor and NASA’s Bridge concept,[26] it is likely that such a rendezvous will become possible in the next decade. This would allow for detailed in situ measurements, which would definitively determine what the galactic census of minor bodies consists of—whether it be hydrogen icebergs from starless cores or artificial relics.

Just as the minor bodies in the solar system have revealed more about its formation than the planets themselves, interstellar objects will reveal more about the constituents of the galaxy than the extrasolar planets and stars. As was the case during the period following the discovery of the first Kuiper belt object, when thousands of trans-Neptunian objects were detected and characterized, we are on the cusp of detecting a wave of these interstellar objects.

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