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INTERSTELLAR OBJECTS FROM BROKEN DYSON SPHERES

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ABSTRACT

Without extensive maintenance, Dyson spheres inevitably disintegrate by asteroid impacts over billions of years. The resulting fragments would appear as anomalous interstellar objects, potentially sharing the unusual shape and motion of 1I/'Oumuamua or the unusual material strength of the first two interstellar meteors, IM1 and IM2. If the Dyson sphere's tiles are light sails, the number of fragments could exceed that of interstellar asteroids because of their reduced escape speed from the star and the increase in stellar luminosity during the red giant phase.

1. INTRODUCTION

In 1937, Olaf Stapledon published the novel "Star Maker", in which he imagined the use of a technologically-manufactored shell of matter to tap the energy output of a host star. The concept was subsequently formalized by Freeman Dyson (Dyson 1960), who reasoned that as the energy needs of humanity will steadily increase, our civilization might aspire to tap all the energy output of the Sun. Dyson proposed a shell of orbiting structures that would intercept and collect the solar luminosity. This so-called Dyson sphere would emit infrared radiation to balance the heat deposited on it by sunlight. The resulting infrared signal could flag a Dyson sphere in contrast to the natural optical emission by Sun-like stars. So far, searches for related infrared signatures from stars or galaxies did not find evidence for Dyson spheres but only for emission by natural dust (see references in Wright (2020)).

Below I demonstrate that if Dyson spheres existed to serve their civilizations for a limited time, most of them would have disintegrated within billions of years in the absence of extensive maintenance. In that case, their ejected fragments could appear as interstellar objects (Siraj & Loeb 2022a).

2. BROKEN DYSON SPHERES

Rigid Dyson spheres are not easy to maintain. In compliance with Newton's iron sphere theorem, a perfectly spherical and rigid shell is not subjected to any net gravitational force from a star interior to it, regardless of whether it is centered on the star. However, the shell experiences destructive differential forces across its surface, and its material strength must be high in order to prevent deformation. The required tensile strength, Π, is given by:

$$\Pi \approx \frac{GM_\star \rho_{ds}}{2R_{ds}} = 3.6 \times 10^6 \text{ MPa} \left(\frac{M_\star}{M_\odot}\right) \left(\frac{\rho_{ds}}{7.9 \text{ g cm}^{-3}}\right) \left(\frac{R_{ds}}{1 \text{ au}}\right)^{-1}, \tag{1}$$

where $M_\star$ is the stellar mass, R_{ds} is the associated Dyson sphere radius and $\rho_{\rm ds}$ is normalized by the solid density of iron. The derived value is an order of magnitude above the tensile strength of graphene, $\Pi_{gr} = 1.3 \times 10^5$ MPa.

The required mass of a Dyson sphere with a thickness W_{ds},

$$M_{ds} = 4\pi R_{ds}^2 W_{ds} \rho_{ds} = 2.3 M_\oplus \left(\frac{R_{ds}}{1 \text{ au}}\right)^2 \left(\frac{\rho_{ds}}{7.9 \text{ g cm}^{-3}}\right) \left(\frac{W_{ds}}{1 \text{ cm}}\right), \tag{2}$$

exceeds the mass of the asteroid belt, 2.4×10^{24} g, by four orders of magnitude. This may explain the inferred discrepancy between the required mass in interstellar objects, such as 1I/'Oumuamua, and the expected mass in asteroids ejected from planetary systems (Moro-Martín et al. 2009; Moro-Martín 2018, 2019).

To circumvent the material strength and mass challenges, Robert Forward proposed a tiled structure (Forward 1991), with each component functioning as a solar sail for which the star's gravity is exactly balanced by by the star's outward radiative push, thus maintaining a fixed position without orbiting the star. The force balance reads (Loeb 2022a):

$$\frac{L_\star}{2\pi R_{ds}^2 c} = \frac{G M_\star \Sigma_{ds}}{R_{ds}^2}, \tag{3}$$

where $L_\star$ is the stellar luminosity and the mass per unit area of the light sail components is given by,

$$\Sigma_{ds} = \rho_{ds} W_{ds} = 1.5 \times 10^{-4}\ \mathrm{g\ cm^{-2}} \left(\frac{L}{L_\odot}\right)\left(\frac{M_\star}{M_\odot}\right)^{-1} . \tag{4}$$

In that case, the required thinness of the Dyson sphere sails could explain (Loeb 2022b; Bialy & Loeb 2018) the flat geometry (Mashchenko 2019) and excess push of the interstellar object 1I/'Oumuamua away from the Sun (Micheli et al. 2018) without a cometary tail (Trilling et al. 2018).

The repulsive push of the stellar radiation pressure is equivalent to a reduction in the effective gravitating attraction of the star because both gravitational and radiative accelerations decline inversely with distance squared. For a ratio $f_{ds} < 1$ between the radiative and gravitational accelerations (the ration between the left and right sides of equation 3), the effective gravitating mass of the star is $(1 - f_{ds})M_\star$. When the two accelerations balance ($f_{ds} = 1$), as considered by equations (3-4), the sail hovers without any gravitational binding to the star. In that case, the escape speed of the sail from the star vanishes, and a small gravitational push outwards by a passing planet could eject it from the planetary system. Consequently, sail fragments would escape much more easily from a planetary system, compared to gravitationally bound asteroids which are trapped by the barrier of a substantial escape speed.

Since sail fragments are thin, they carry much less mass than asteroids of the same length, thus relieving the mass discrepancy associated with interstellar asteroids (Moro-Martín et al. 2009; Moro-Martín 2018, 2019).

Both radiative and gravitational forces are spherically symmetric as long as the sail maintains a fixed cross-sectional area in the direction of the star. This can be trivially accomplished by a sail in the shape of a small sphere which maintains a constant cross-sectional area irrespective of orientation.

Even without damage from asteroids, abandoned sails will eventually be pushed out of the planetary system as a sun-like star would evolve through its red giant phase, resulting in an increase in its luminosity-to-mass ratio.

3. IMPLICATIONS

If a Dyson sphere disintegrated by asteroid impacts over time, then its fragments would have been ejected by a gravitational or radiative push out of the host planetary system more easily than asteroids.

Interstellar fragments of a broken Dyson sphere could potentially share the unusual shape (Mashchenko 2019) and light sail characteristics of the interstellar object 1I/'Oumuamua (Loeb 2022b; Bialy & Loeb 2018), or the unusually high yield strength ($\gtrsim 10^2$ Mpa, larger than the value of iron meteorites) exhibited by the first and second interstellar meteors, IM1 and IM2 (Siraj & Loeb 2022b). The planned expedition to retrieve the fragments of IM1 (Siraj et al. 2022) and the subsequent analysis of the fragments composition, could potentially test this hypothesis.

Irrespective of its architecture, maintenance of a Dyson sphere is extremely challenging since the structure will be punctured by a few billion human-size asteroids every year for a planetary system that resembles the Solar system. Over a few billion years, the structure would have holes of a few meters in size every hundred meters. Interestingly, the estimated size of 1I/'Oumuamua was about a hundred meters (Mashchenko 2019), potentially dictated by the asteroid bombardment rate of an old Dyson sphere in a Sun-like planetary system.

Small holes would be more abundant. The holes would cover a significant fraction of the Dyson sphere surface from bombardment by micrometeorites on sub-centimeter scales. This impact statistics is currently measured empirically, as JWST is being hit by a dust-sized particle every month. Without repair, a billion-year old Dyson sphere would resemble a fishing net which lets a substantial fraction of the starlight out.

In summary, once a civilization abandons its Dyson sphere this technosignature is expected be punctured by micrometeorites and lose its functionality on a timescale much shorter than the lifetime of the host star. Studies of the composition of interstellar objects offers a new way to constrain the abundance of broken Dyson spheres, irrespective of their age and deteriorated infrared characteristics.

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REFERENCES

Bialy, S., & Loeb, A. 2018, ApJL, 868, L1, doi: 10.3847/2041-8213/aaeda8

Dyson, F. J. 1960, Science, 131, 1667, doi: 10.1126/science.131.3414.1667

Forward, R. L. 1991, Journal of Spacecraft and Rockets, 28, 606, doi: 10.2514/3.26287

Loeb, A. 2022a, Research Notes of the American Astronomical Society, 6, 104, doi: 10.3847/2515-5172/ac72ad

—. 2022b, Astrobiology, 22, 1392, doi: 10.1089/ast.2021.0193

Mashchenko, S. 2019, MNRAS, 489, 3003, doi: 10.1093/mnras/stz2380

Micheli, M., Farnocchia, D., Meech, K. J., et al. 2018, Nature, 559, 223, doi: 10.1038/s41586-018-0254-4

Moro-Martín, A. 2018, ApJ, 866, 131, doi: 10.3847/1538-4357/aadf34

—. 2019, AJ, 157, 86, doi: 10.3847/1538-3881/aafda6

Moro-Martín, A., Turner, E. L., & Loeb, A. 2009, ApJ, 704, 733, doi: 10.1088/0004-637X/704/1/733

Siraj, A., & Loeb, A. 2022a, Astrobiology, 22, 1459, doi: 10.1089/ast.2021.0189
—. 2022b, ApJL, 941, L28, doi: 10.3847/2041-8213/aca8a0
Siraj, A., Loeb, A., & Gallaudet, T. 2022, arXiv e-prints, arXiv:2208.00092, doi: 10.48550/arXiv.2208.00092
Trilling, D. E., Mommert, M., Hora, J. L., et al. 2018, AJ, 156, 261, doi: 10.3847/1538-3881/aae88f
Wright, J. T. 2020, Serbian Astronomical Journal, 200, 1, doi: 10.2298/SAJ2000001W