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Scientific Critique, Debate and Commentary

A NOTE ON THE VUKOTIĆ-GORDON MINI-EARTHS

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SUMMARY: A recent proposal for a new kind of astroengineering artifact due to Vukotić and Gordon (2022) is discussed, in particular in light of multiple benefits offered by the magnetic Penrose process. It is argued that constructing a large number of artifacts of this kind is sufficiently strongly motivated for any advanced extraterrestrial society that their statistical weight in the set of all technosignatures will be significant. This will, in turn, have important consequences for our practical SETI/search for technosignatures projects.

Key words. Astrobiology – Extraterrestrial intelligence – Black hole physics – Magnetic fields – Methods: analytical

1. INTRODUCTION: MINI-EARTHS

The search for technosignatures is one of the foremost aspects of the astrobiological research today (Wright et al. 2022). Many different technosignatures have been proposed since Dyson's seminal 1960 paper on the eponymous spheres (Dyson 1960; cf. Wright 2020. Proposals include stellar nuclear waste dumps (Whitmire and Wright 1980); artificial transiting objects (Arnold 2005); shell-worlds (Birch 1991, Roy et al. 2009); stellar engines (Badescu and Cathcart 2000); solar shields/orbital mirrors/solettas/shielding swarms (Loeb and Turner 2012, Lior 2013, Ćirković and Vukotić 2016); bulk antimatter-burning engines (Harris 1986, 2002); laser-beam leakage (Guillochon and Loeb 2015); missing stellar objects (Villarroel et al. 2016), and many others. One speculative suggestion close to the topic of the present study is a kind of "anti-Dyson" sphere or swarm, created around a black hole (Inoue and Yokoo 2011, Opatrný et al. 2017, Hsiao et al. 2021). In general, fascination with black holes and their possible relationship to astrobiology and SETI studies has often appeared throughout the literature in recent years (e.g., Bakala et al. 2020).

In a similar spirit, Vukotić and Gordon (2022) propose *mini-Earths*: rocky objects – say asteroids or cometary nuclei – of 100km or so in diameter, with small black holes inserted in their centers of mass, providing several advantages for habitation and industry. One such advantage is increased gravity, which could be fine-tuned to be as close to the Earth's gravity as desired. Therefore, a breathable atmosphere could be retained over the surface of such a body, in spite of its small size. Earth-like gravity – and adjustable gravity in general – could, of course, have other astromedical advantages from the point of view of those humans born and raised in strong gravitational potential wells. Altogether, the concept of mini-Earth is a wonderful example of the exploratory engineering in the sense of Armstrong and Sandberg (2013): "The art of figuring out what techniques are compatible with known physics, and could plausibly be reached in the future by human scien-

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tists. …results that are beyond what is currently possible, but that are likely to be achieved by future civilisations" (p. 2).

Vukotić and Gordon, however, do undersell their idea, since it has other appealing features not mentioned in their brief paper. The present work attempts to rectify this omission and to argue that mini-Earths are indeed promising technosignatures to search for, reflecting to a lesser degree the same property of *technological convergence* Dyson spheres are justly praised for (Wright 2020). In other words, there are additional advantages and incentives for any extraterrestrial technological society to build them – and in large numbers. The foremost reason is using the Penrose process – in one of its many versions – for obtaining useful energy, as well as removing industrial pollution and waste, possible computational uses and magnetic shielding; this will be discussed in Section 2. Some other merits of the proposal will be considered in Section 3. The discussion in Section 4 will bring reader's attention to one interesting description of mini-Earth-like artifact from the treasure trove of SF literature, before giving some summarizing comments and suggestions for future research.

2. PENROSE PROCESS: THREE BIRDS WITH ONE STONE

With the "black hole revolution" in 1960s and the advent of black hole thermodynamics in 1970s, there came some ingenious ideas of extracting energy from rotating (Kerr) black holes. The pioneering work of Sir Roger Penrose (1969, see especially the last couple of pages and the exciting Figure 5, subsequently reproduced or redrawn many times; Penrose and Floyd 1971) brought attention to the fact that within the ergosphere of a Kerr black hole there are orbits with negative total energy with respect to an observer at infinity. This does not violate energy conservation, which is defined locally, as the energy with respect to the local frame of reference; the latter of necessity has nonzero angular velocity $\omega = -g_{03}/g_{33}$ in spherical coordinates with indices $(0, 1, 2, 3)$ corresponding to (ct, r, θ, φ). This constitutes the famous frame-dragging effect of general relativity.

The presence of negative energy orbits within the ergosphere enables the extraction of energy in the following manner. Suppose the particle 1 with the total energy E_1 moves on such an orbit and subsequently decays into two particles (2 and 3) with energies E_2 and E_3. Obviously, in a local frame of reference, $E_1 = E_2 + E_3$. It is then possible that particle 2 falls into the black hole, while particle 3 escapes to infinity with energy larger than that of the original particle 1. The energy efficiency of this process, conventionally defined as the ratio of extracted to infalling energy is given by (e.g., Tursunov and Dadhich 2019):

$$\begin{aligned}\eta &= \frac{E_3 - E_1}{E_1} = \frac{1}{2}\left(\sqrt{\frac{2M}{r}} - 1\right)\\ &\approx \frac{M}{2a}\left(\sqrt{2}\sqrt{1 - \sqrt{1 - \frac{a^2}{M^2}}} - \frac{a}{M}\right). \qquad (1)\end{aligned}$$

Here, M is the black hole mass, a its angular momentum, r the radial distance at which the split occurs, $G = c = 1$, and the latter equation is valid for the split occurring very close to the event horizon $(r \to 0)$. For extremal Kerr black holes $a = M$ and the efficiency maximizes at $\eta = 21\%$. While this is high enough in comparison to conventional energy-extracting processes such as coal burning $(\eta \sim 10^{-8})$, uranium fission $(\eta \sim 0.1\%)$, or thermonuclear fusion $(\eta \sim 1\%)$, it is an idealized case unlikely to be realistic in either astrophysical or technological applications (Wald 1974, Bravetti et al. 2016, Leiderschneider and Piran 2016).

This is, however, an estimate based on reversible, infinite-time thermodynamics. For finite-time processes, Bravetti et al. (2016) find that their average energy efficiency increases with increasing black hole mass. Below about $10^{30}\,M_{Pl}$ the process is inefficient, since more work has to be supplied from the environment than is obtained by removal of angular momentum ($M_{Pl} \approx 2.18 \times 10^{-8}$ kg being the Planck mass; for comparison, $1\,M_\oplus = 2.7 \times 10^{32}\,M_{Pl}$). This is exactly the range of interesting black hole masses, so we can expect the efficiency to be $\eta \sim 1\%$. While this seems small, it is still similar to stellar fusion of hydrogen, while having much higher energy density – and being able to use practically any kind of matter as fuel.

Subsequently, many different forms of the Penrose process have been identified and studied, in particular the *collisional* Penrose process (in which multiple particle collisions occur within the ergosphere, with the center-of-mass energy growing arbitrarily high for extremal Kerr black holes) and the *magnetic* Penrose process (which includes the interaction of matter with the electromagnetic field surrounding black hole). The latter is particularly relevant for small black holes necessary for mini-Earths, as will be outlined below.

A particular subtype of the magnetic Penrose process is the Blandford-Znajek mechanism, which occurs with strong magnetic fields in the plasma surrounding a rotating black hole. A situation similar to the classical Faraday disc then occurs: a black hole's rotation generates electric currents along the horizon (or close) surface, which effectively converts mechanical spin energy into electromagnetic energy to be extracted. The threshold magnetic field strength is of the order of 10^4 G, which is realistic for the active galactic nuclei environment (Blandford and Znajek 1977). It is usually stated by critics that such strong magnetic fields are likely to decay quickly in typical astrophysical environments – which is beyond the point for the case of mini-Earths and similar artificial environments.[1]

The efficiency of the magnetic Penrose process is given as the sum of the "classical" mechanical part of Eq. (1) which peaks at about 21% and the magnetic part which is linear in black hole mass, angular momentum and magnetic field strength at the point of particle split (Tursunov and Dadhich 2019):

$$\eta_{\rm MPP} = \frac{1}{2}\left(\sqrt{\frac{r_G}{r_s}} - 1\right) + \frac{q_3 G M B a}{m_1 c^4}\left(1 - \frac{r_G}{2r_s}\right). \quad (2)$$

Here, $r_G \equiv 2GM/c^2$ (in SI or cgs units) is the gravitational radius here best understood as the radius of the ergosphere, r_s is the radius at which particles split, m_1 is the infalling particle mass and q_3 is the electric charge of the outgoing particle. Clearly, the electromagnetic term can become very large for strong magnetic fields and supermassive black holes. A process like the pair production, which produces electrons (or positrons) as the outgoing particles, can reach maximal efficiencies on the order unity even for sub-Earth-mass black holes of $M \sim 10^{-6}\ M_\odot$ and for moderately strong magnetic fields of $B \sim 10^4$ G. Thus, while *extremely* high values of energy efficiency required for e.g., acceleration of ultrahigh-energy cosmic-ray particles are available only from supermassive black holes in centres of galaxies, even small black holes could achieve significant values. What makes this process of energy extraction especially appealing from a technological point of view is that for small black holes the magnetic field needs to be maintained only in a very small spatial volume – and can, moreover, be easily modulated in order to adapt efficiency in any particular moment of time.

Consider for instance the case of fiducial mini-Earth discussed by Vukotić and Gordon with radius of $R = 60$ km. Both "thin" and "thick" variants are possible, the minimal thickness being constrained by elasticity of the material necessary to prevent buckling (Wright 2020). Vukotić and Gordon show that this minimal thickness is of the order of 10 m if the best currently known materials are used. In the thin version, gravity from the shell itself would be completely negligible. On the other hand, the thick version could use a spherical cavity inside an asteroid with thickness on the order of tens of kilometers, which would contribute ~1% to the total surface gravity (with natural densities of M type asteroids about $5 - 6 \times 10^3\ \mathrm{kg\,m^{-3}}$). The rest would come from the central black hole of the mass on the order of $10^{19} - 10^{20}$ kg, which is on the order of 10% of the mass of large asteroids such as 2 Pallas or 4 Vesta. Building for smaller surface gravity, for example 50% of the standard g, would reduce the black hole mass required (although, as mentioned above, the energy efficiency decreases sharply with the decreasing black hole mass). There are many interesting issues related to the exploratory engineering of such habitats to be discussed, which go beyond the scope of the present manuscript.

On the other hand, we reemphasize that conventional criticisms of the Blandford-Znajek mechanism as applied to astrophysical phenomena such as jets and outflows in the active galactic nuclei, such as those of Livio et al. (1999) are *not* applicable to artificially created situations. High values of energy efficiency found by researchers for idealized situations could occur here, although they are unlikely to be realized in nature. This is similar to the situation occurring with natural nuclear fission reactors: while such phenomena could in principle occur, the conditions are rather restrictive, requiring fine-tuning of some of the parameters, so it is not very surprising that only one such case, Oklo in Gabon, has been discovered so far on our planet and within its entire geological history (Gauthier-Lafaye et al. 1996). In contrast, man-made nuclear fission reactors are a common occurrence, many hundreds of them being present in a negligibly short span of time from Fermi's Chicago Pile-1 to this day.

Of course, no matter which type of the Penrose process one wishes to deploy, at least part of the matter infalling from effective infinity will be thrown into the black hole and irretrievably lost. As Penrose originally suggested half-jocularly, garbage cans could be launched in such a manner that they release their contents toward the event horizon and are subsequently picked by a contraption converting their boosted kinetic energy into electricity. Even if central black holes need to be manufactured *ab initio*, one could think about them as batteries, releasing slowly and in a controlled manner part of the large amount of energy expended in their creation.

This type of matter-to-energy conversion has several merits of interest for exploratory engineers. In contrast to technogenic nuclear fission or fusion, black holes will convert matter of *any* chemical composition into energy, since gravitational field couples to any kind of mass or energy. In contrast to natural (stellar) nuclear fusion, black holes will work at any location, irrespective of the distance from one's home star – or indeed any star whatsoever. Power production ("luminosity") of the central black hole engine could be roughly estimated from the energy conservation:

$$\varepsilon \dot{E}_{BH} = \dot{E}_{th} + \dot{E}_{pr} + \dot{E}_{st}, \quad (3)$$

where E_{th} denotes the thermal energy radiated by the habitat, E_{pr} is the energy required for its propulsion, and E_{st} is the energy stored in various ways, including the fraction fed back into the black hole (in-

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[1] Notice that in both these cases magnetic fields are considered to be weak in a sense that their contribution to the total stress-energy tensor $T^{\mu\nu}$ does not change the background (Kerr-Newman) metric. This applies equally to the natural and artificial magnetic fields, since only at the critical value of about 10^{18} G magnetic effects on metric become non-negligible.

tentionally or not; cf. Opatrný and Richterek 2012, Opatrný et al. 2017); ε is the dimensionless *capture* efficiency in the mini-Earth context, as distinct from the standard energy extraction efficiency η. Neglecting E_{pr} and E_{st} in the first approximation and assuming that mini-Earth as a whole radiates according to the Stefan–Boltzmann law with the constant σ, we can constrain the mass consumption rate of the central black hole engine. With $\dot{E}_{BH} = \eta \dot{m} c^2$ this mass consumption rate obtains as:

$$\dot{m} = \frac{4\pi\sigma}{c^2} \eta^{-1} \varepsilon^{-1} R^2 T^4 \tag{4}$$

For fiducial values of $R = 60$ km, $T = 300$ K, $\eta = 0.01$, and $\varepsilon = 0.5$, we obtain $\dot{m} \approx 46.2$ g s^{-1}, (about 1500 tonnes per year), which looks reasonable and shows that high-efficiency black hole engine could supply power for cosmological durations. Of course, other terms on the right-hand side of Eq. (3) could increase the mass-burning rate of the black-hole engine (though increases in η and ε could decrease the rate as well). In general, the omnivorous mass consumption is modest; if a mini-Earth is constructed by hollowing out and reshaping an asteroid, the loss of useful mass would be negligible even over millions of years. For instance, 253 Mathilde which is similar in size to our fiducial mini-Earth would lose only about 1.5×10^{-5} of its mass *per million years* through the process described by Eq. (4).[2] And the small consumption rate is to be compared with rather unwieldy amounts of hydrogen (or, even worse, deuterium or ^{3}He) one needs to produce the analogous power through controlled thermonuclear fusion.

Obviously, one need not use useful mass – in the "having-other-functions" sense of useful – but presumably unrecyclable residual waste of the technological civilization instead, as per the original Penrose suggestion. While it is hard to discern how much waste will a very advanced society of Kardashev Type 2 or higher produce, especially in terms of recycling efficiency for cultures possessing efficient nanotechnology or femtotechnology, one could try to very roughly extrapolate. How big is human present-day waste production? Global reports are largely inconsistent, but a recent meta-study gives it as 2.1 billion tonnes of solid waste in 2018 (Maalouf and Mavropoulos 2023); projections for 2050 give numbers like 3.5 billion tonnes (Chen et al. 2020). While there are indications that this quantity increases slower than global GDP or other economic parameters, there is no doubt that it increases with time.

Humanity as of recently is a Kardashev Type 0.73 civilization (Kardashev 1964, 1985, Ćirković 2015; check also https://ourworldindata.org/energy-production-consumption, last accessed September 20, 2023). The rough formula would be:

$$n = 1 + \frac{1}{10} \log_{10} \left(\frac{P}{10^{16}\, W} \right), \tag{5}$$

where P is the managed power and $n$is the Kardashev Type. If we suppose that solid waste production is proportional to the energy managed/dissipated in the sense of Kardashev, reaching Type 2 status – prototypical for the era of the Dyson sphere construction – would imply producing mass of solid waste equal to about 4.4×10^{22} tonnes yr^{-1} $\approx 7.4\, M_\oplus$ yr^{-1}(!). Even 99.99% efficient recycling would still require Type 2 civilization to dispose of several times 10^{18} tonnes of waste per year. If converted to energy via the Penrose process with modest efficiency of $\eta = 2\%$, this amount of waste would still outshine the Sun hundreds of times – thus making, seemingly paradoxically, such a future civilization *higher* on the Kardashev's Scale than Type 2. Obviously, a truly sustainable future society will require both drastic reduction of bulk waste production *and* asymptotic recycling efficiency in order to cope with the astronomical amount of waste generated by industrial civilization – and still, waste removal through a version of the Penrose process will be quite efficient way of generating useful work.

Note that it is widely recognized that what is called "waste to energy" is an important task for the present-day and near-future global human civilization (e.g., Castaldi 2021). There is no reason to doubt that it will remain an active and persistent problem for more advanced technological societies. Entirely new forms of waste – like e-waste in recent years (e.g., Thakur and Kumar 2022) – will likely appear and require safe disposal, and perhaps serve as a source of energy. All these needs will be efficiently satisfied by various forms of the Penrose process, in which waste could be disposed of in a highly controlled manner beneath the event horizon. Even waste *heat* of industrial or computational processes could be, at least in principle, dumped into the black hole due to their exceedingly low horizon temperatures, as discussed in detail in the colourful study of Opatrný et al. (2017).

Which brings us to another potential advantage of using the magnetic Penrose process within Vukotić-Gordon mini-Earths: the very same capacity to manipulate magnetospheric currents and to create poloidal magnetic field around a spinning black hole will enable astroengineers of the future (or those of advanced extraterrestrial civilizations) to create a magnetosphere of the mini-Earth itself. The latter is clearly important protection against a part of the cosmic ray energy distribution, thus adding to the atmospheric protection against ionizing radiation. It is not necessary to elaborate in any detail how high ionizing flux has deleterious effects on various lifeforms, including causing cell and DNA damage, various cancerogenic and mutagenic processes, and adverse chemical reactions in the atmosphere or hydrosphere. Magnetic shielding against at least a part of the cosmic ray influx would, therefore, be a desir-

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[2] Using the data presented by `https://nssdc.gsfc.nasa.gov/planetary/factsheet/asteroidfact.html`, last accessed December 4, 2023.

able side effect of maintaining and managing strong magnetic fields within mini-Earths.

3. ERGODICITY OF TECHNOLOGY AND FURTHER MERITS OF THE MINI-EARTH CONCEPT

The advantages described in the previous section clinch the argument of Vukotić and Gordon (2022) for the mini-Earth as a useful and probably convergent form of astroengineering artifacts and technosignatures worth searching for in our SETI efforts. This is not the end of the story, since there are further desirable features of the envisioned mini-Earths, both from the construction and from the motivational points of view.

As Vukotić and Gordon note (p. 75), the expenditure of matter for constructing a mini-Earth with the surface area comparable to that of Belgium is very modest indeed. The real question, however, is whether producing a large number of mini-Earths is the optimal manner of usage for a (nearly) fixed amount of matter available in the Solar System or in any analogous habitable planetary system in the Galaxy. This is a part of the more general question about the hierarchy of technologies required for a particular set of technosignatures. While everyone would agree that details of technological development will be quite different at various locales in the Galaxy and for different extraterrestrial intelligent species, the question whether the general shape of technological development could be radically different from what we expect on the basis of our limited historical experience is still very much open. In other words, it is unclear whether technological evolution is globally ergodic or not; or at least whether ergodicity is valid at scales more fine-grained than the Kardashev Scale.

There are some arguments for non-ergodicity of technological evolution on Earth; we have commented briefly upon such items elsewhere in the context of evaluating technosignature artifact claims (Ćirković 2023). In his last great novel, *Fiasco*, Stanislaw Lem envisioned technological civilization whose development took a radically different direction from the one on Earth (Lem 1987). For instance, the Quintans are masters of nanopolymers, material science and physical chemistry, clearly superior to the (future) human abilities in those areas; and yet, humans are much more powerful militarily due to their insights into quantum gravity and corresponding technologies such as the "gravitational laser" and similar devices. Both here and in his discoursive writing, Lem has criticized the orthodox SETI position which has traditionally assumed ergodic technological development with its insistence on targeted radio-messaging.

So, is there a necessary hierarchy of technologies ranging all the way to astroengineering or megaengineering constructions? Is building a Dyson sphere either conceptually or practically more demanding or advanced than creating artificial black holes? Are the two even comparable, in the sense that there is a universal set of criteria to compare them? And even if we could, for instance, argue that one is indeed easier than the other, is that a sufficient reason to believe that all hypothetical instances of extraterrestrial civilizations will follow the predicted pathway? While there may be some indications or arguments either way, we surely lack clear-cut answers to these questions. In such a situation, it seems rationally justified to speculate and compare various astroengineering options and scenarios in terms of material or energy costs involved.

Suppose, for simplicity, that we compare a single Dyson sphere or radius R_{DS} and the thickness d_{DS} with a set of N mini-Earths with the average radius $\langle R_{mE}\rangle$ and average thickness $\langle d_{mE}\rangle$. If we consider just the *volume* of the construction material and under plausible assumptions $R_{DS} \gg d_{DS}$ and $\langle R_{mE}\rangle \gg \langle d_{mE}\rangle$, and neglect black hole masses for the moment, the same amount of material is expended for:

$$N = \left(\frac{R_{DS}}{\langle R_{mE}\rangle}\right)^2 \frac{d_{DS}}{\langle d_{mE}\rangle}. \tag{6}$$

For $R_{DS} = 1\text{AU}$ and $\langle R_{mE}\rangle = 60\text{km}$ (as suggested by Vukotić and Gordon, p. 74), with the thickness ratio denoted by $\xi \equiv d_{DS}/\langle d_{mE}\rangle$, this becomes $N = 6.25 \times 10^{12}\,\xi$. Even for much smaller Dyson sphere radii and thicknesses, and taking into account matter necessary for black hole production, it is clear that large number of mini-Earths could be constructed *in lieu* of a Dyson sphere. If black holes are constructed from the same matter, Eq. (6) may be modified as:

$$N = \frac{R_{DS}^2 d_{DS}}{\langle R_{mE}\rangle^2 \langle d_{mE}\rangle + \frac{\langle m_{BH}\rangle}{4\pi\rho}}, \tag{7}$$

where it is assumed that the density of shells is the same for both Dyson sphere and mini-Earths $\rho_{DS} = \rho_{mE} = \rho$, and the ensemble-average of black hole masses is $\langle m_{BH}\rangle$.

If it is surface area that we are primarily interested in (the "real estate"), the ratio of surface area of the Dyson sphere and the set of mini-Earths utilizing the same amount of matter in approximation Eq. (6) obtains simply as ξ^{-1}. Thin-shell kind of mini-Earths will, thus, be in the same ballpark as the Dyson sphere as far as the surface area is concerned. This is deceptive, however, since even if Dyson spheres could be constructed as solid shells (which is not realistic, as known since the original proposal and elaborated by Wright 2020), this would not really be *habitable* surface area, in contrast to mini-Earths which offer the entire $4\pi\langle R_{mE}\rangle^2 N$ of habitable surface area with gravity, potentially breathable atmosphere, a realistic habitat for flora and fauna, etc.

None of this would be available on the Dyson sphere without additional massive engineering feats – some of which, like localized gravity control, might not be even physically possible. Also, the level of matter processing would likely be rather different, and also favoring mini-Earths over the Dyson sphere. In the first approximation, a mini-Earth could plausibly be just a hollowed-out and mechanically strengthened asteroid or a cometary nucleus – while there is no celestial body which could be continuously transformed into a Dyson sphere.

On the other hand, the two astroengineering proposals are in fact not so antithetical. Mini-Earths could equally well serve as components of a Dyson *swarm* (Smith 2022), thus joining the Solar energy gathering function of the Dyson sphere to their other merits. The construction timescale for individual mini-Earth would presumably be much shorter than for larger astroengineering contraptions, so that there is economic utility in developing the swarm over a longer period of time and benefitting from experience and the iterative improvement of construction techniques.

It is likely that artificially created black holes will be of the kind usable for computational purposes. Speculative possibilities in this regard have been discussed, among others, by Sandberg (2000), Ng (2001) or Vidal (2012). There is a wide array of computational prospects which could be realized in due course when construction of mini-Earths becomes routine. Other important experiments or phenomena related to physics close to the event horizon could be either researched or deployed for industrial purposes in a mini-Earth environment (e.g., those related to the Tolman temperature gradient; see Santiago and Visser 2019).

One may envision various kinds of mini-Earths, depending on their main purpose: in addition to serving as habitats, industrial bases, research centres, refuelling stations for interplanetary and interstellar travel, artistic colonies, sport facilities, or even natural preserves or long-term repositories of advanced knowledge (cf. Guzman et al. 2017). Just like the original O'Neill colonies (O'Neill 1977), it is both quality *and* diversity of uses and lifestyles enabled by mini-Earths which is one of the major arguments in favour of the concept.

It is possible that the central black hole engine could be used for moving a mini-Earth around or for station keeping if necessary. This is grounded in the study of Crane and Westmoreland (2009), cited also by Vukotić and Gordon; see also Crane (2010) and Vidal (2012). There are multiple examples of this idea in the SF discourse, most notably Sir Arthur C. Clarke's too often underestimated classic *Imperial Earth* (Clarke 1975) and a modern rendition by the Canadian hard SF author Peter Watts in his complex *Freeze-Frame Revolution* (Watts 2018). While using the central black hole in this manner might be possible – whether it makes practical sense for mini-Earths is less clear, in light of the fact that propulsion would at the very least require a nozzle or a funnel isolated from the atmosphere, leading to obvious technical difficulties.

A related speculative possibility would be to use the black hole gravity lens, producing what is in optics called an axicon (McLeod 1954), for astronomical observations of distant sources with an extreme magnification. Obviously, this would entail either removal of selected parts of the mini-Earth crust or devising a way for making them transparent. The latter could be achieved with smart matter with adjustable refraction index, which is subject of much contemporary work in nanotechnology (e.g., Xia et al. 2018, Kang et al. 2020). The advantage here would be the usage of the same high-precision position control necessary for other mini-Earth-related functions, while benefitting from Newton's iron sphere theorem (or Birkhoff's relativistic generalization thereof) safety-wise. An externally placed black hole would attract both the habitat and particles in the interplanetary medium, thus obstructing astronomy and risking damage to the habitat; internal placement would, seemingly paradoxically, be safer due to the vanishing of gravitational attraction between the spherically-symmetric habitat and the black hole.[3]

4. DISCUSSION

As in many other cases, art has been ahead of science on the technosignature front. In his brilliant 2008 novel *House of Suns*, Welsh author Alastair Reynolds, probably the most distinguished representative of the "new space opera" movement, offers a dual narrative of one Abigail Gentian living in the 31^{st} century and her siblings/clones travelling the Galaxy about 6,000,000 years hence, largely due to relativistic time-dilation (Reynolds 2008). As a posthuman youngster and scion of one of the wealthiest families in the industrialized Solar System, Abigail lives in a "house with a million rooms" (p. 3; *not* to be taken literally!) which is about the only building on a planetoid with standard gravity. Subsequently, it is explained that it contains a small black hole in its centre of mass, thus being a fine fictional description of the mini-Earth concept.[4]

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[3] As a related curiosity, the first major European observatory in modern sense of the word, Tycho's Stjerneborg on the island of Ven, was built mostly *underground*. The main reason was strong winds blowing in the Öresund strait and interfering with delicate observational instruments such as triangular sextants and armillaries, but also with observers and their health in long and cold nights amidst northern seas (wonderful history is given in Thoren and Christianson 1990).

[4] Early on, another character tells Abigail that "the thing down there" is dangerous (p. 6), but it's more a part of childish teasing, than a real risk assessment; in any case, no technical difficulty or danger is mentioned anywhere else. (It is unclear, however, why Reynolds chose to have no atmosphere at Abigail's mansion planetoid, in spite of its standard gravity; the puzzle is compounded by very specific insistence on the architecture being adapted to weather circumstances down to "a steep-sided, blue-tiled roof" [p. 4].)

To summarize, mini-Earths are a novel and promising kind of both astroengineering projects for future humanity and technosignatures to be searched for in our SETI efforts. Mini-Earths have multiple highly desirable features, such as possibility of being self-sufficient energy-wise on long timescales (and thus potentially located in any region of any planetary system, or even in the interstellar or intergalactic space), capacity of converting industrial waste to energy, capacity for extremely advanced propulsion and computing, etc.

A particular advantage of mini-Earths would be their capacity to function as habitats – or cargo vessels – at large distances from the home star or even in the interstellar space. The amount of matter consumed in order to provide heating and other forms of energy in those circumstances is minuscule in comparison to its total structural mass. One could even envision chains of mini-Earths providing a kind of island-hopping pathways between the neighbouring planetary systems or toward nearest brown dwarfs/rogue planets which turn out to be quite numerous in the Galaxy (Strigari et al. 2012). Therefore, it makes sense to look for these technosignatures in dark and cold spaces beyond the realm of planets in the candidate exoplanetary systems. While more detailed models are required to predict their exact technosignature profile, it makes sense to assume that a mini-Earth at e.g., 300 K will be an outlying source in $\sim$10 K Oort Cloud/interstellar space, more prominent than a similar artifact located within the noisy domain of planets and asteroids.

A recent speculative and fascinating idea that at least some technologies are convergent, rather than contingent, features of the universe at large (Shainline 2020) provokes many questions about the place of mind and technology on the cosmological scales. While a general criticism could be levelled against any concept involving artificial creation and manipulation of black holes, we are perhaps still technologically too immature to be able to recognize the entire wide spectrum of their usefulness. If black holes belong to *attractors in the parameter space of all possible technologies*, then reflecting on their placement within the set of technosignatures to be sought for sounds like a reasonable proposition. (Obviously, this pertains with equal force to both future human astroengineering achievements and those of advanced extraterrestrial civilizations; cf. Ćirković 2018.) If mini-Earths of Vukotić and Gordon belong to this category, as their multiple advantages elaborated above seem to suggest, then it justifies formulating specific observational proposals for seeking them. Of course, more quantitative research is certainly needed to establish in detail how particular spectral or photometric signatures of mini-Earths could be detected.

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БЕЛЕШКА О ВУКОТИЋ-ГОРДОНОВИМ МИНИ-ЗЕМЉАМА

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Разматрамо скорашњи предлог за нову врсту астроинжењерских артефаката који су дали Вукотић и Гордон (2022), нарочито у светлу вишеструких предности које нуди магнетски Пенроузов процес. Сугеришемо да постоји довољно снажна мотивација за било коју напредну ванземаљску цивилизацију да конструише велики број артефаката ове врсте, тако да ће они имати значајну тежину у скупу свих техносигнатура. Ово, са своје стране, има значајне последице по наше практичне SETI пројекте и пројекте потраге за техносигнатурама.