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A Dyson sphere around a black hole

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ABSTRACT

The search for extraterrestrial intelligence (SETI) has been conducted for nearly 60 yr. A Dyson sphere, a spherical structure that surrounds a star and transports its radiative energy outwards as an energy source for an advanced civilization, is one of the main targets of SETI. In this study, we discuss whether building a Dyson sphere around a black hole is effective. We consider six energy sources: (i) the cosmic microwave background, (ii) the Hawking radiation, (iii) an accretion disc, (iv) Bondi accretion, (v) a corona, and (vi) relativistic jets. To develop future civilizations (for example, a Type II civilization), 4×10^{26} W($1\,\mathrm{L}_\odot$) is expected to be needed. Among (iii) to (vi), the largest luminosity can be collected from an accretion disc, reaching $10^5\,\mathrm{L}_\odot$, enough to maintain a Type II civilization. Moreover, if a Dyson sphere collects not only the electromagnetic radiation but also other types of energy (e.g. kinetic energy) from the jets, the total collected energy would be approximately 5 times larger. Considering the emission from a Dyson sphere, our results show that the Dyson sphere around a stellar-mass black hole in the Milky Way (10 kpc away from us) is detectable in the ultraviolet (10−400 nm), optical (400−760 nm), near-infrared (760 nm−5 μm), and mid-infrared (5−40 μm) wavelengths via the waste heat radiation using current telescopes such as *Galaxy Evolution Explorer* Ultraviolet Sky Surveys. Performing model fitting to observed spectral energy distributions and measuring the variability of radial velocity may help us to identify these possible artificial structures.

Key words: extraterrestrial intelligence – accretion, accretion discs – space vehicles – stars: black holes – quasars: supermassive black holes.

1 INTRODUCTION

Since the very early stage of human history, our ancestors have already imagined the existence of aliens. Numerous science fiction movies, television series, and fiction have demonstrated extraterrestrial intelligence in different forms. However, even to this day, the debate on the existence of aliens or extraterrestrial intelligence in reality continues. Despite the controversy, the search for extraterrestrial intelligence (SETI) has been conducted since the 1960s (Project Ozma).[1] Fortunately, after around 30 yr since SETI began, the first exoplanet (Gamma Cephei Ab) was discovered (Campbell, Walker & Yang 1988), and a new window was opened for the search for extraterrestrial life. In the next decade, the *James Webb Space Telescope* (*JWST*) plans to study the atmosphere of the exoplanet. Hence, *JWST* has a potential to reveal the origin of life and find extraterrestrial intelligence.[2] Although there have hitherto been negative results, it never diminishes human curiosity in SETI.

Many studies discussed and provided different concepts related to the advanced civilizations (e.g. Dyson 1960a; Shkadov 1988; Lee 2013). One of the most famous concepts is the ‘Dyson sphere’, which was first described by Dyson (1960a). Dyson (1960a) argued that if there was an advanced civilization in the Universe, it must consume extremely high energy to maintain itself. In such a civilization, its parent star (the star which its planets orbit around) could be a candidate to provide ample energy for development and sustainability. Assuming that the highly-developed civilization is eager to absorb the energy from its sun, a Dyson sphere is a spherical structure that fully surrounds the star and directs all the radiative energy outward. For instance, if a Dyson sphere is built around the Sun, the total luminosity of the Sun ($\mathrm{L}_\odot \sim 4 \times 10^{26}$ W) can be utilized, which is approximately nine orders of magnitude larger than the power intercepted by the Earth ($\sim 1.7 \times 10^{17}$ W). After receiving the energy from the star, the civilization would be able to convert the energy from low-entropy to high-entropy and emanate

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[1] https://www.seti.org/seti-institute/project/details/early-seti-project-ozma-arecibo-message

[2] https://www.jwst.nasa.gov/content/science/origins.html

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the waste heat (e.g. in mid-infrared wavelengths) into the background, suggesting this kind of energy waste is detectable (Dyson 1960a).

However, building a rigid Dyson sphere is almost mechanically impossible due to the gravity and the pressure from the central star (e.g. Wright 2020). Hence, some variants of the concept were proposed. For instance, a Dyson Swarm[3] is a group of collectors that orbits the central energy source (see also Dyson 1960b). This method allows the civilization to grow incrementally. Nevertheless, due to the orbital mechanics, the arrangement of such collectors would be extraordinarily complex. Another variant is a Dyson Bubble[3] which contains a host of collectors as well. However, the collectors are instead stationary in space assuming equilibrium between the outward radiative pressure and the inward gravity, which are usually called 'solar sails' or 'light sails'.

Based on energy consumption, Kardashev (1964) classified the hypothetical civilizations into three categories (Kardashev scale). A Type I civilization uses infant technology and consumes 4×10^{16} W (or 4×10^{23} erg s^{-1})[4], the energy of its planet. A Type II civilization harvests all the energy of its parent star, namely 4×10^{26} W (or 4×10^{33} erg s^{-1}). A Type III civilization represents the highest technological level, which can engulf its entire galaxy as its energy source. A typical energy used by a Type III civilization is about 4×10^{37} W (or 4×10^{44} erg s^{-1}). To represent the civilizations that have not been able to use all of their available energy sources, Sagan (1973) suggested a logarithmic interpolation in the form of $K = 0.1(\log P - 6)$, where K is the Kardashev index and P (in the unit of Watts) indicates the energy consumption. Currently, our civilization level is approximately 0.73[5]. We may become a Type I civilization in 200–800 yr, a Type II in 1000–3000 yr, and a Type III in 2000–5000 yr, assuming the energy consumption increases by 1–3 per cent yr^{-1} (e.g. Gray 2020).

The purpose of this study is to discuss the possibility of black holes being a candidate for an energy source to build a Dyson sphere of a civilization between Type II and Type III ($2 < K < 3$; a Type II civilization). As we mentioned in the previous paragraph, after a Type II civilization absorbs all the energy from the parent star, a Type II civilization would seek another star to maintain itself. We would like to answer the question if black holes can be regarded as proper energy sources, or if they are inefficient to provide ample energy for civilizations to thrive. Inoue & Yokoo (2011) discussed a similar idea by describing a Dyson sphere around a supermassive black hole (SMBH). They assumed the energy from the accretion disc of an SMBH as the only energy source for a Type III civilization. Their Dyson sphere (collectors of power plants) is located between the accretion disc and the molecular torus, and is built to partly cover an SMBH to avoid absorbing the piercing jets to melt the Dyson sphere. However, the possibility to detect these structures is extremely low (the chance to detect an unexpected signal from 1 μas is less than 10^{-23}; Inoue & Yokoo 2011).

Moreover, Opatrný, Richterek & Bakala (2017) discussed a Dyson sphere which absorbs the energy from the cosmic microwave background (CMB). Compared with the CMB, a black hole should be a 'cold' sun, turning the idea of the Dyson sphere inside out (Here we name it as the inverse Dyson sphere; IDS). Based on their results, a black hole with one solar mass could only provide (literally the CMB provides $T_{\rm CMB} = 2.725$ K) 250 W in the recent Universe. If there is an SMBH in the early Universe ($z \sim 109$) with a habitable temperature $T_{\rm CMB} = 300$ K (Loeb 2014), it would provide $\sim 3\times10^{20}$ W. However, compared to a main-sequence star (e.g. $1\,{\rm L}_\odot = 4\times10^{26}$ W), this available energy is much less.

In this paper, we consider and discuss six types of energy sources: the CMB, the Hawking radiation, an accretion disc, Bondi accretion, a corona, and the relativistic jets from two types of black holes: a non-rotating black hole (Schwarzschild black hole) and a rotating black hole (Kerr black hole), ranging from micro, stellar-mass, intermediate-mass to SMBH (i.e. 10^{-5}–$10^{10}\,{\rm M}_\odot$). The structure and outline of this paper are as follows: we discuss the possible energy sources from a black hole in Section 2. In Section 3, we describe the possible location, type, efficiency, and detectability of such a Dyson sphere. The conclusion of this study is presented in Section 4.

2 ENERGY SOURCE

In this section, we demonstrate six energy sources if a Type II civilization aims to build a Dyson sphere around a black hole. In this paper, we utilize the terminologies 'promising' and 'enough' to indicate when the energy is larger than one solar luminosity for a Type II civilization. We mainly discuss three scenarios: two stellar black holes with masses 5 and $20\,{\rm M}_\odot$, and an SMBH with mass $4\times10^6\,{\rm M}_\odot$. Their physical parameters are organized in Table 1.

2.1 Cosmic microwave background

The CMB is the remnant temperature from the early Universe which is an evidence of the big bang. In the mid-20th century, Gamow (1948) predicted the existence of the CMB while its first measurement was conducted later by Penzias & Wilson (1965). Here, we show the possibility for a Dyson sphere to collect the CMB energy.

In principle, the CMB is hotter than a black hole (discussed in Section 2.2). Opatrný et al. (2017) discussed the concept that a Dyson sphere absorbs energy from the hot CMB and emits waste energy into a cold black hole. Opatrný et al. (2017) derived the limiting power from the CMB for a Dyson sphere as

$$P_{\rm max} \sim \frac{27}{256}\sigma S T_{\rm CMB}^4, \text{ where } S = 4\pi\left(\frac{\sqrt{27}}{2}R_{\rm Sch}\right)^2 = \frac{108\pi G^2M^2}{c^4}, \tag{1}$$

where σ is the Stefan–Boltzmann constant, S indicates the surface area of the black hole while $T_{\rm CMB}$ is the temperature of CMB, $R_{\rm Sch}$ stands for the Schwarzschild radius, G is the gravitational constant, M indicates the mass of the black hole, and c is the light speed in the vacuum.

According to Loeb (2014), the habitable epoch of the Universe starts around when the temperature of the CMB is $T_{\rm CMB} = 300$ K. For this purpose, we also discuss the early Universe when the CMB temperature is 300 K. The following two conditions, recent Universe with $T_{\rm CMB} = 2.725$ K (Fixsen 2009) and habitable Universe with $T_{\rm CMB} = 300$ K of $P_{\rm max}$ can be written in the following numerical form, respectively:

$$\frac{P_{\rm max}(2.725\,{\rm K})}{\rm Watt} \sim 2.45\times10^2\left(\frac{M}{{\rm M}_\odot}\right)^2, \tag{2}$$

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[3] https://www.aleph.se/Nada/dysonFAQ.html

[4] In Kardashev (1964)'s original definition, a Type I civilization consumes an energy of that close to a planet, i.e. 4×10^{12} W. Nowadays, a Type I civilization is usually defined as harvesting all the power of a planet.

[5] According to the world energy report of 2020: https://www.bp.com/content/dam/bp/business-sites/en/global/corporate/pdfs/energy-economics/statistical-review/bp-stats-review-2020-full-report.pdf, the total world energy consumption in 2019 is 583.9 exajoule ($\sim 1.85\times10^{13}$ W).

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Table 1. Three scenarios of a Dyson sphere around a black hole at different efficiency.

Scenario	A (stellar-mass black hole)	B (stellar-mass black hole)	C (SMBH)
Mass ($\mathrm{M}_{\odot}$)	5	20	4×10^{6}
Eddington ratio ($\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}}$)	10^{-2}	10^{-1}	10^{-3}
Schwarzschild radius (km)	14.77	59.08	1.18×10^{7}
Dyson sphere radius at $T = 3000$ K (R_{sch})	7.12×10^{6}	1.13×10^{7}	2.54×10^{3}
Disc luminosity[a]	1.6×10^{3} (2.38)	6.4×10^{4} (2.54)	1.3×10^{8} (2.87)
Total luminosity[a]	3.5×10^{3} (2.41)	1.4×10^{5} (2.57)	2.8×10^{8} (2.90)
Total power[a]	1.7×10^{4} (2.48)	6.1×10^{5} (2.63)	1.1×10^{9} (2.96)
50 per cent efficiency			
Disc luminosity[a]	800 (2.35)	3.2×10^{4} (2.51)	6.4×10^{7} (2.84)
Total luminosity[a]	1750 (2.38)	6.9×10^{4} (2.54)	1.4×10^{8} (2.87)
Total power[a]	8450 (2.45)	3.1×10^{5} (2.61)	5.5×10^{8} (2.93)
10 per cent efficiency			
Disc luminosity[a]	160 (2.28)	6.4×10^{3} (2.44)	1.3×10^{7} (2.77)
Total luminosity[a]	350 (2.31)	1.4×10^{4} (2.47)	2.8×10^{7} (2.80)
Total power[a]	1690 (2.38)	6.1×10^{4} (2.54)	1.1×10^{8} (2.86)
1 per cent efficiency			
Disc luminosity[a]	16 (2.18)	6.4×10^{2} (2.34)	1.3×10^{6} (2.67)
Total luminosity[a]	35 (2.21)	1.4×10^{3} (2.37)	2.8×10^{6} (2.70)
Total power[a]	169 (2.28)	6.1×10^{3} (2.44)	1.1×10^{7} (2.76)

[a] Numbers outside parentheses are in units of $L_{\odot}$, while numbers inside the parentheses are in units of Kardashev index.

and

$$\frac{P_{\max}(300\,\mathrm{K})}{\mathrm{Watt}} \sim 3.59 \times 10^{10} \left(\frac{M}{\mathrm{M}_{\odot}}\right)^{2}. \tag{3}$$

We caution readers that black holes when $T_{\mathrm{CMB}} = 300$ K ($z \sim 109$) were probably primordial black holes since the first stars are thought to have formed afterwards (e.g. Carr & Hawking 1974). If a Type II civilization wants to harvest the CMB power , no matter in the recent or early Universe, the power is too low to maintain a Type II civilization. Even in the early stage of the Universe, we need to find an SMBH ($M > 10^{8}\,\mathrm{M}_{\odot}$) to gain the energy of a solar luminosity, which seems to be inefficient.

2.2 Hawking radiation

Hawking (1974) predicted and derived the theory of blackbody radiation emitted from outside the event horizon of a black hole, which was named 'Hawking radiation'. Although there is no direct detection hitherto, it is a result of the quantum effects and expected to reduce the black hole mass.

Based on Hawking (1974), the temperature of a Schwarzschild black hole can be expressed as

$$T_{\mathrm{Sch}} = \frac{\hbar c^{3}}{8\pi k_{\mathrm{B}} G M}, \tag{4}$$

where $\hbar$ is the reduced Planck constant, and k_{B} stands for the Boltzmann constant. Nevertheless, we calculate the power of blackbody luminosity ($L_{\mathrm{Hawking}} = 4\pi R_{\mathrm{Sch}}^{2} \sigma T_{\mathrm{Sch}}^{4}$) of Hawking radiation as follows (e.g. Lopresto 2003):

$$L_{\mathrm{Hawking}} = \frac{\hbar c^{6}}{15360\pi G^{2} M^{2}} \sim 9.00 \times 10^{-29} \left(\frac{M}{\mathrm{M}_{\odot}}\right)^{-2} \mathrm{Watt}. \tag{5}$$

The total radiation from a black hole itself is extremely low.

In terms of a rotating black hole, the temperature of the Hawking radiation from a rotating black hole (here we assume Kerr–Vaidya metrics) can be expressed as follows (e.g. Chou 2020):

$$T_{\mathrm{Kerr}} = \gamma \frac{\hbar c^{3}}{8\pi k_{\mathrm{B}} G M}, \text{ where } \gamma = \frac{\sqrt{1 - a^{2}}}{1 + \sqrt{1 - a^{2}}}, \tag{6}$$

where a stands for the spin parameter of a black hole. As the spin parameter increases, the factor γ decreases. We conclude that collecting the Hawking radiation from a Kerr black hole is harder than a Schwarzschild black hole (although both ways are almost impossible). We will not discuss the luminosity of a Kerr black hole further since it is harder to harvest the energy from a Kerr black hole.

2.3 Accretion disc

The massive object in the centre would accrete the gas and the material close to it into a vortex disc. Due to the strong gravity from a black hole, the material in an accretion disc would be heated by friction. After the igniting process, an accretion disc emits strong radiation. Hence, a Type II civilization could harvest the radiation from the accretion disc.

We first consider the Eddington luminosity of a black hole in different mass ranges (Rybicki & Lightman 1979):

$$L_{\mathrm{Edd}} = \frac{4\pi G M m_{\mathrm{p}} c}{\sigma_{\mathrm{T}}} \sim 3.2 \times 10^{4} \left(\frac{M}{\mathrm{M}_{\odot}}\right) \mathrm{L}_{\odot}, \tag{7}$$

where m_{p} suggests the mass of a proton, and σ_{T} is Thomson scattering cross-section ($\sigma_{\mathrm{T}} = 6.65 \times 10^{-29}\,\mathrm{m}^{-2}$). The result suggests that if a Type II civilization finds a black hole with accretion disc reaching the Eddington limit, even if the black hole is only the size of a stellar black hole ($5\,\mathrm{M}_{\odot} < M < 20\,\mathrm{M}_{\odot}$), it could provide up to $\sim 10^{5}\,\mathrm{L}_{\odot}$. Additionally, we consider the luminosity as a function of mass accretion rate:

$$L_{\mathrm{disk}} = \eta_{\mathrm{disk}} \frac{\mathrm{d}m}{\mathrm{d}t} c^{2}, \tag{8}$$

where η_{disc} is the accretion efficiency, *dm/dt* indicates the mass accretion rate. According to Thorne (1974), the accretion efficiencies of different types of black holes are $\eta_{\mathrm{disc}} = 0.057$ for a Schwarzschild black hole and $\eta_{\mathrm{disc}} = 0.399$ for an Extreme Kerr black hole ($a = 1$),

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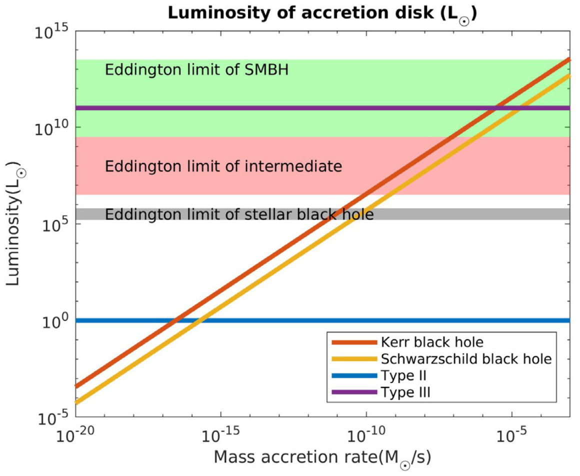

Figure 1. Accretion disc luminosity as a function of the mass accretion rate. The orange line suggests $\eta = 0.399$, which is the case of the extreme Kerr black hole ($a = 1$), while the yellow line shows $\eta = 0.057$, which is the case of non-rotating black holes. The blue line and the purple line indicate the required energy of a Type II and a Type III civilizations, respectively. Shaded regions suggest Eddington luminosity limits of different types of black hole: grey for stellar-mass black holes ($5\,\mathrm{M}_\odot < M < 20\,\mathrm{M}_\odot$), red for intermediate-mass black holes ($10^2\,\mathrm{M}_\odot < M < 10^5\,\mathrm{M}_\odot$), and green for SMBHs ($10^5\,\mathrm{M}_\odot < M < 10^9\,\mathrm{M}_\odot$).

respectively. Adopting these efficiencies, we calculate the luminosity at different accretion rates. The result is shown in Fig. 1. The different coloured regions indicate the Eddington limit of stellar-mass black holes ($5\,\mathrm{M}_\odot < M < 20\,\mathrm{M}_\odot$), intermediate-mass black holes ($10^2\,\mathrm{M}_\odot < M < 10^5\,\mathrm{M}_\odot$), and SMBHs ($10^5\,\mathrm{M}_\odot < M < 10^9\,\mathrm{M}_\odot$). The results suggest that even for a stellar-mass black hole with a low Eddington ratio (10^{-3}), the luminosity of the accretion disc is several hundred times of a solar luminosity.

Furthermore, an intermediate-mass black hole with a high accretion rate would emit an energy up to $\sim 10^9\,\mathrm{L}_\odot$, which is only 1 per cent of the required energy of a Type III civilization. At the same mass accretion rate, the luminosity of an extremely Kerr black hole accretion disc is seven times larger than the Schwarzschild black hole due to the accretion efficiency. Therefore, we conclude that the accretion discs of both types of black holes (non-rotating and extremely rotating) have the potential as a Type II civilization's energy source.

2.4 Bondi accretion

Bondi accretion is a spherical gas accretion on to a compact gravitating object from the interstellar medium with no angular momentum and no magnetic field (Hoyle & Lyttleton 1939; Bondi 1952). Considering the Bondi accretion around the vicinity of black holes, the analytical solution of the luminosity from Bondi accretion can be expressed as follows:

$$L_{\mathrm{Bondi}} = \eta c^2 \left(\frac{\pi G^2 M^2 \rho}{c_{\mathrm{s}}^3} \right), \tag{9}$$

where L_{Bondi} is the luminosity of Bondi accretion, ρ is the ambient density, and c_{s} is the sound speed. The sound speed in a gas cloud can be expressed as follows:

$$c_{\mathrm{s}} = \sqrt{\frac{k_{\mathrm{B}} T_{\mathrm{gas}}}{\mu m_{\mathrm{H}}}}, \tag{10}$$

where T_{gas} is the temperature of the gas, μ is molecular weight, and m_{H} is mass of a hydrogen atom. Adopting $\mu = 1$, $m_{\mathrm{H}} = 1.67 \times 10^{-27}$ kg, $T_{\mathrm{gas}} = 10^7$ K for the SMBH (e.g. Di Matteo et al. 2003) and $T_{\mathrm{gas}} = 10^4$ K for the stellar-mass black holes (e.g. Alvarez, Wise & Abel 2009), and $\rho = 1.67 \times 10^{-27}\,\mathrm{kg/cm^3}$, the Bondi luminosity can be expressed as

$$L_{\mathrm{Bondi}} \sim 2.8 \times 10^3 \left(\frac{M}{\mathrm{M}_\odot} \right)^2 \left(\frac{n}{\#/\mathrm{cm}^3} \right) \left(\frac{T}{\mathrm{K}} \right)^{-3/2}. \tag{11}$$

For scenarios A, B, and C, we obtained 0.07, 1.11, 1.40 × $10^6\,\mathrm{L}_\odot$, respectively. These are $\sim 10^{-6}$ and ~ 1 per cent of their accretion disc luminosities for the stellar-mass black holes and the SMBH, respectively. These radiative energies are too faint compared to the energy from the accretion disc.

2.5 Corona

The gas around a black hole is in the plasma state due to the high temperature from the accretion disc, and this surrounding gas is called the corona. Meanwhile, the corona generates high energy radiation as well (e.g. Haardt & Maraschi 1993). Thus, the radiation from the corona could be a good candidate in providing additional energy, aside from the radiation from the accretion disc.

For simplicity, we adopt the empirical relation between the corona luminosity and the disc luminosity from Sazonov et al. (2012):

$$\log \left(\frac{L_{\mathrm{corona}}}{10^{44}\ \mathrm{erg\ s^{-1}}} \right) = 1.03 \log \left(\frac{L_{\mathrm{disc}}}{10^{44}\ \mathrm{erg\ s^{-1}}} \right) - 0.207, \tag{12}$$

where L_{corona} represents the luminosity of corona in the unit $10^{44}\ \mathrm{erg\ s^{-1}}$. This relation is the best fit of the luminosity of hot corona versus disc luminosity using 60 active galactic nuclei from International *Gamma-Ray Astrophysics Laboratory* (*INTEGRAL*) all-sky hard X-ray survey. The samples have similar X-ray flux variations with X-ray binaries, which can be expressed as a lognormal distribution. We assume that this formula extends to different mass ranges including stellar-mass black holes (e.g. Uttley, McHardy & Vaughan 2005). For a stellar-mass black hole, the corona luminosity is approximately one-third of the radiation from the accretion disc while the ratio between the corona luminosity and the accretion disc luminosity increases to 1/2 for an SMBH. If a Type II civilization includes the corona luminosity as well, the useful energy becomes 1.3–1.5 times of the accretion disc luminosity, which would be another promising energy source for maintaining civilization.

2.6 Relativistic jets

Relativistic jets are high-energy and piercing phenomena, which are common among compact objects. These plasma flow contain tremendous energy and are usually along the axis of rotation of the object. The particles inside the jets could reach the Lorentz factor up to 100 ($\gamma = (\sqrt{1 - v^2/c^2})^{-1}$). Although the relation between the accretion disc and the relativistic jets is not clear so far, it is believed that the jets are driven by the tangled magnetic field (e.g. Blandford & Znajek 1977; Hawley & Balbus 2002; McKinney & Gammie 2004).

For simplicity, according to Ghisellini et al. (2014), the radiation of relativistic jets has an empirical relation with the luminosity of the accretion disc for an SMBH as follows:

$$\log \left(\frac{L_{\mathrm{jets}}}{\mathrm{erg\ s^{-1}}} \right) = 0.98 \log \left(\frac{L_{\mathrm{disc}}}{\mathrm{erg\ s^{-1}}} \right) + 0.639, \tag{13}$$

where L_{jets} is the electromagnetic radiation of the jets. This relation is based on the least-squares best fit of the radiative jet power

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versus disc luminosity using objects detected with *Fermi*/Large Area Telescope (LAT) and spectroscopic optical observations. Most of the Eddington ratios of the samples are in the range between 1 per cent to 100 per cent, suggesting that the discs are geometrically thin, (e.g. Shakura & Sunyaev 1973). X-ray binaries in the soft state are usually in this case (e.g. Fender 2002). Therefore, we assume that this empirical formula holds in different mass ranges. A stellar-mass black hole with a low Eddington ratio can even produce several orders of solar luminosity, suggesting that the energy in jets has the potential to provide the energy required by a Type II civilization.

According to equation (13), the radiation from the jets would be $\sim$80 and $\sim$60 per cent of the radiation from an accretion disc for a stellar-mass black hole and an SMBH, respectively. In addition, the radiation from the jets is believed to be $\sim$10 per cent of the total energy of jets (e.g. Ghisellini et al. 2014). If the technology is able to collect the energy from not only the luminosity but also the total energy of the jets, the energy available would be 10 times larger. According to our results, only with the mass $M = 0.003\,\mathrm{M}_\odot$ and Eddington ratio $= 10^{-3}$, could the energy reach one solar luminosity. For a stellar-mass black hole with $5\,\mathrm{M}_\odot$, the total jet energy becomes $\sim 1.7 \times 10^6\,\mathrm{L}_\odot$. The results suggest that the relativistic jets could be promising sources in the Universe regardless of the high temperature.

3 DYSON SPHERE

In this study, we only discuss the civilizations which were born and raised from other stars. We speculate that this kind of civilization can collect the energy remotely or treat the energy source as a power station rather than living around a black hole with a harsh environment. Therefore, throughout the paper, we do not discuss whether the temperature and the gravity of our configurations are suitable for life (e.g. Schwartzman 1977; Inoue & Yokoo 2011). Moreover, we discuss two scenarios for the Dyson sphere: (1) assuming that a Type II civilization has the technology advanced enough to afford extreme high temperatures (hot Dyson sphere hereafter) and (2) the realistic solid material to avoid melting $T \sim 3000\,\mathrm{K}$ (solid Dyson sphere hereafter)[6].

3.1 Possible type and location

In reality, a monolithic Dyson sphere is mechanically unstable due to the pressure and the gravity from the central star (e.g. Wright 2020). Hence, a structure similar to a Dyson Swarm or a Dyson Bubble becomes a more promising candidate to collect energy. Moreover, considering a Type II civilization might want to transfer energy from jets as well, a Dyson Bubble would be a more possible case to collect the energy from jets since the celestial mechanics of a Dyson Swarm is complicated and chaotic. Therefore, we discuss two scenarios for a Dyson sphere. At the early stage of building a Dyson sphere, the most simplified configuration is a Dyson Ring (a type of a Dyson Swarm), which contains numerous collectors sharing the same orbit.

Taking the widely discussed stellar-mass black hole, Cygnus X-1, as an example (e.g. Shapiro, Lightman & Eardley 1976; Ichimaru 1977; Fabian et al. 1989), with the mass of $M = 8.7\,\mathrm{M}_\odot$ (Iorio 2008), the accretion disc extends to $r \sim 500 R_{\mathrm{Sch}}$ (Young et al. 2001). For a simplified discussion, we assume the inner radius of the accretion disc is around $R_{\mathrm{in}} = 3R_{\mathrm{Sch}}$, which is the radius outside the innermost stable circular orbit (ISCO) of a Schwarzschild black hole. In terms of the outer radius of the accretion disc, which has not been studied well so far, we assume its outer radius extends to $R_{\mathrm{out}} = 1000 R_{\mathrm{Sch}}$ (e.g. Inoue & Yokoo 2011; You, Cao & Yuan 2012). For a stellar-mass black hole, since its accretion disc size is smaller than the size of the Sun, the radius of its Dyson sphere is smaller than that of a stellar Dyson sphere ($R_{\mathrm{out}} = 1\,\mathrm{AU}$ corresponds to $M = 5 \times 10^4\,\mathrm{M}_\odot$). At this stage, the possible radius for the Dyson sphere to collect the energy from the accretion disc should be around $10^3 R_{\mathrm{Sch}} < R_{\mathrm{DS}} < 10^5 R_{\mathrm{Sch}}$, which locates outside the accretion disc. If a Dyson sphere is constructed farther away from the accretion disc, the efficiency may be too low (e.g. if two Dyson spheres of the same size are built at distances of $10^3 R_{\mathrm{Sch}}$ and $10^6 R_{\mathrm{Sch}}$, respectively, the latter one could only intercept 10^{-6} times the energy of the former one), and might crush into the dusty torus.

For a given black hole mass, luminosity, and temperature for a Dyson sphere to afford, we can rewrite the luminosity of a spherical blackbody ($L = 4\pi\sigma R^2 T^4$) into the following form to calculate the radius of a Dyson sphere in units of R_{Sch}:

$$\left(\frac{R_{\mathrm{DS}}}{R_{\mathrm{Sch}}}\right) = \frac{c^2}{2GM}\sqrt{\frac{L_{\mathrm{disc}}}{4\pi\sigma T^4}} \sim 8.01 \times 10^{12}\left(\frac{M}{\mathrm{M}_\odot}\right)^{-1} \times \left(\frac{L}{\mathrm{L}_\odot}\right)^{\frac{1}{2}}\left(\frac{T}{\mathrm{K}}\right)^{-2}, \tag{14}$$

where T is the temperature a Dyson sphere wants to absorb rather than emitting. In terms of the solid material which can absorb ~ 3000 K, the Dyson sphere should be located at $R_{\mathrm{DS}} \gtrsim 7.12 \times 10^6 R_{\mathrm{Sch}}$ and $R_{\mathrm{DS}} \gtrsim 1.13 \times 10^7 R_{\mathrm{Sch}}$ for Scenarios A and B, respectively, to avoid melting. For an SMBH, Scenario C, the Dyson sphere could be set at $R_{\mathrm{DS}} \gtrsim 2.54 \times 10^3 R_{\mathrm{Sch}}$.

Not surprisingly, if a Type II civilization wishes to build a Dyson sphere receiving $T = 3000\,\mathrm{K}$ and $1\,\mathrm{L}_\odot$, the total area required is independent from the mass of the source black hole (or a star), which is $\sim 8.65 \times 10^{19}\,\mathrm{m}^2$. Compared to the total area ($7.03 \times 10^{22}\,\mathrm{m}^2$) of the Dyson sphere around the Sun at 1 AU, this area is $\sim$100 times smaller. Indeed, if the Dyson sphere is closer to the black hole, the temperature is higher but the needed surface area decreases. However, the maximum luminosity a Type II civilization can absorb is different.

In terms of energy from jets, utilizing the pressure that balances the inward gravity and without the need to be in orbit (stationary in space), a Dyson Bubble is considered to be built with a huge amount of light sails. First of all, we consider the balance between different types of pressures and the gravitational force from a black hole:

$$F_{\mathrm{G}} = \oint_S (p_{\mathrm{rad}} + p_{\mathrm{dyn}} + p_{\mathrm{B}})\,\mathrm{d}s, \tag{15}$$

where S is the surface area of a light sail, and the notations of p stands for different types of pressure outwards: radiation pressure [$p_{\mathrm{rad}} \propto I \propto R_{\mathrm{DS}}^{-2}$; I: flux (W m^{-2})], dynamical pressure [$p_{\mathrm{dyn}} \propto \rho v^2 \propto R_{\mathrm{DS}}^{-3}$; ρ: density of the jets, and v: speed of jets], and magnetic pressure ($p_{\mathrm{B}} \propto B^2 \propto R_{\mathrm{DS}}^{-4}$; B: magnetic flux density). Note that R_{DS} stands for the distance of the Dyson sphere to the black hole rather than the radius of the light sail itself. Along the path of jets, pressure decreases as radius increases ($p_{\mathrm{total}} \propto \frac{c_1}{R_{\mathrm{DS}}^2} + \frac{c_2}{R_{\mathrm{DS}}^3} + \frac{c_3}{R_{\mathrm{DS}}^4}$, where c_1, c_2, and c_3 represent the coefficients of different types of pressures). Moreover, the increase of the surface area of a light sail increases the outward force on the sail. The surface area of a light sail is proportional to R_{DS}^2 if a light sail is designed to cover the whole opening angle of the jet, which leads to $F_{\mathrm{G}} \propto \frac{m}{R_{\mathrm{DS}}^2} \propto R_{\mathrm{DS}}^2\left(\frac{c_1}{R_{\mathrm{DS}}^2} + \frac{c_2}{R_{\mathrm{DS}}^3} + \frac{c_3}{R_{\mathrm{DS}}^4}\right)$. Considering an outward pressure and inward gravitational force, the mass m required to build a light sail would be smaller when a light sail is closer to the black hole ($m \propto c_1 R_{\mathrm{DS}}^2 + c_2 R_{\mathrm{DS}}^1 + c_3$). Thus, to save the materials,

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[6] https://pubchem.ncbi.nlm.nih.gov/compound/23964

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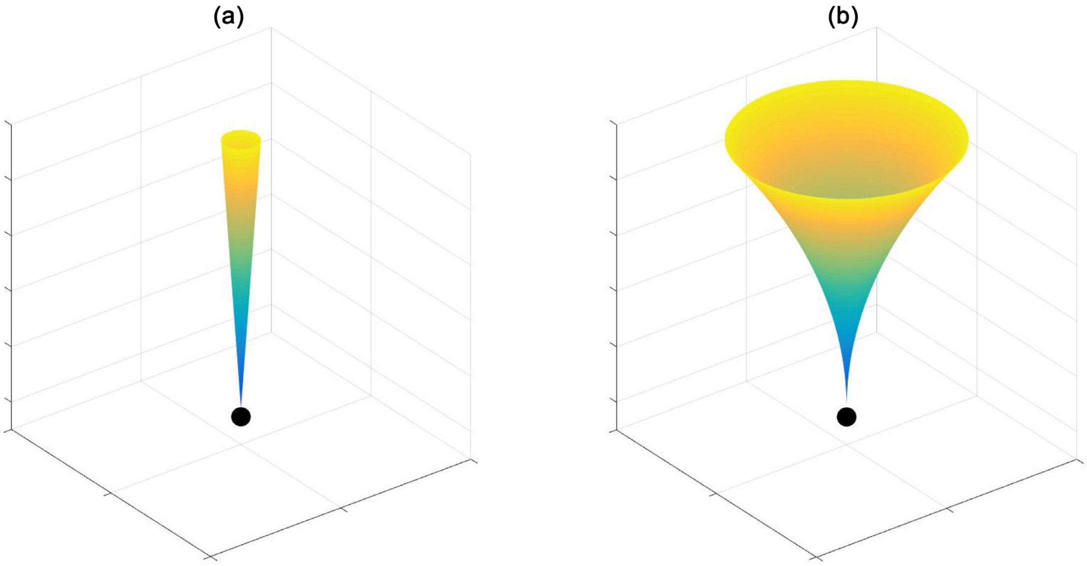

Figure 2. Schematic of the relativistic jets. (a) Linear transmission of jets (i.e. the surface area $\propto R_{\mathrm{DS}}^2$) and (b) with changing angle (i.e. the surface area $\propto R_{\mathrm{DS}}^k$, here $k = 4$). The colour scales with the distance from the black hole. Scales are arbitrary. The panels are not to scale.

it is better to locate a light sail close to where the jets originate from no matter how large the coefficients are.

If the jet opening angle also changes with the radius, we assume $S \propto R_{\mathrm{DS}}^k$, where S is the surface area of a light sail and k is an arbitrary real number. Equation (15) becomes $\frac{m}{R_{\mathrm{DS}}^2} \propto R_{\mathrm{DS}}^k(\frac{c_1}{R_{\mathrm{DS}}^k} + \frac{c_2}{R_{\mathrm{DS}}^{k+1}} + \frac{c_3}{R_{\mathrm{DS}}^4})$. Regardless of the value of k, the mass of a light sail required decreases at the location closer to the origin of the jets. These two scenarios are visualized in Fig. 2. Fig. 2(b) shows the schematic of changing angle jets described by an arbitrary power law. Under these assumptions, a Type II civilization could build a light sail with fewer materials. However, a Type II civilization needs to consider the ISCO ($r = \frac{6GM}{c^2}$ and $r = \frac{GM}{c^2}$ for a Schwarzschild black hole and an extreme Kerr black hole, respectively) if a Type II civilization wants to collect energy *in situ* instead of remotely. However, we caution readers that the luminosity of accretion discs of black holes varies with time. Accretion discs switch between bright and dim states (e.g. Done, Gierliński & Kubota 2007). If the accretion disc becomes too bright, the structures might be blown away while if the accretion disc gets too faint, the Dyson sphere may fall into the black hole.

3.2 Efficiency

Even in reality, considering the transfer efficiency and the covering fraction, the accretion disc could still play a pivotal role for a Type II civilization. We combine two concepts, energy transfer efficiency and the sky covering fraction, into the terminology ‘efficiency’ (e.g. if a Dyson sphere covers 10 per cent of the sky and 50 per cent of energy transfer to usable energy, the efficiency is 5 per cent). Most of the solar cell efficiency on the Earth reaches 15 per cent. In the world record, the highest efficiency is ∼47 per cent (Geisz et al. 2018). For instance, if there is a 50 per cent energy-conversion efficiency in the future, a Dyson sphere covering 2 per cent of the sky can extract 1 per cent available energy from the 5 $\mathrm{M}_{\odot}$ black hole. This corresponds to 16 $L_{\odot}$ which is sufficient for a Type II civilization. In this case, only 10 per cent surface area of the Earth is needed to cover the 2 per cent of the sky at a distance of $r_{\mathrm{out}} = 1000R_{\mathrm{Sch}}$.

Assuming a Type II civilization collects the energy from a $5\,\mathrm{M}_{\odot}$ black hole with a low Eddington ratio ($\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}} = 10^{-2}$), the total luminosity from the accretion disc is $1600\,\mathrm{L}_{\odot}$ ($\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}} \times L_{\mathrm{Edd}}$). Moreover, if a Type II civilization could find a stellar-mass black hole with higher Eddington ratio ($\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}} = 10^{-1}$) and larger mass ($M = 20\,\mathrm{M}_{\odot}$), the total available energy from the accretion disc is $6.4 \times 10^4\,\mathrm{L}_{\odot}$. In other words, the accretion disc alone can provide sufficiently enormous luminosity to be collected by a Type II civilization. If a Type II civilization could find such a way, it could utilize an accretion disc rather than hunting ten thousand stars. The black hole could play an important role for a Type II civilization whether or not they just reach a Type II civilization or will soon become a Type III civilization. Furthermore, if a Type II civilization becomes a Type III civilization in a short period, it will likely seek an SMBH located at the galactic centre such as Sgr A∗ in the Milky Way. If an SMBH with the mass ($M = 4 \times 10^6\,\mathrm{M}_{\odot}$) and low Eddington ratio ($\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}} = 10^{-3}$), the total luminosity from the accretion disc is $10^8\,\mathrm{L}_{\odot}$, or 10^{34} W, which makes up 0.025 per cent of the required by a Type III civilization (4×10^{37} W). It would be much more efficient than collecting a host of stars distributed in a galaxy.

Additionally, if a Type II civilization not only absorbs the energy from an accretion disc but also collects the radiation from a corona and relativistic jets, the available energy would be larger. We consider two kinds of energy: total luminosity ($L_{\mathrm{total}} = L_{\mathrm{disc}} + L_{\mathrm{corona}} + L_{\mathrm{jets}}$) and total energy including the kinetic energy of the jet ($P_{\mathrm{total}} = P_{\mathrm{jets}} + L_{\mathrm{total}}$). For the first scenario ($5\,\mathrm{M}_{\odot}$ and $\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}} = 10^{-2}$), if 1 per cent energy could be transferred to usable energy, the usable energy are $L_{\mathrm{total}} \sim 35\,\mathrm{L}_{\odot}$ and $P_{\mathrm{total}} \sim 169\,\mathrm{L}_{\odot}$ while Kardashev indices could reach $K = 2.21$ and $K = 2.28$. As for the second scenario ($20\,\mathrm{M}_{\odot}$ and $\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}} = 10^{-1}$), the total luminosity and the total power are $1.4 \times 10^5\,\mathrm{L}_{\odot}$ and $6.1 \times 10^5\,\mathrm{L}_{\odot}$, which could boost the civilization up to $K = 2.57$ and $K = 2.63$. In the last scenario for the SMBH ($4 \times 10^6\,\mathrm{M}_{\odot}$ and $\frac{L_{\mathrm{disk}}}{L_{\mathrm{Edd}}} = 10^{-3}$), the total power is $\sim 10^9\,\mathrm{L}_{\odot}$, giving $K \sim 3$. We organize different configurations of power for three scenarios with different efficiencies in Table 1.

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3.3 Detectablility

In terms of detectability, direct evidence from a Dyson sphere seems to be impossible because even if a Type II civilization covers 90 per cent of the luminosity from the accretion disc, we can only expect an Eddington ratio 10 times smaller. For instance, if there is a black hole with the Eddington ratio $\frac{L_{\rm disk}}{L_{\rm Edd}} = 10$ per cent in the true Universe and a Type II civilization covers 90 per cent of the luminosity from the accretion disc, we would falsely measure the Eddington ratio of this black hole as 1 per cent.

A more promising way to detect Dyson spheres is from the waste heat in IR. After utilizing the energy, the wasted IR energy would be released to the background by a typical Dyson sphere. Here we calculate the spectrum of an accretion disc with a Dyson sphere. We assume multicolour blackbody radiation (e.g. Mitsuda et al. 1984; Makishima et al. 1986; Merloni, Fabian & Ross 2000) for the disc spectrum:

$$f_{\rm disc} = \frac{\cos(\theta)}{D^2}\int_{r_{\rm in}}^{r_{\rm out}} 2\pi r B(T(r))\,{\rm d}r, \tag{16}$$

adopting the temperature profile $\propto r^{-3/4}$ (optically thick, geometrically thin accretion disc). $f_{\rm disc}$ is the flux of the accretion disc. θ stands for the inclination angle of the disc ($\theta = 0^\circ$ in our spectrum), D is the distance between the observer and the disc, while $B(T(r))$ is the Planck function. The luminosity of an accretion disc is as follows:

$$L_{\rm disc} = \int_{r_{\rm in}}^{r_{\rm out}} 4\pi r\sigma T(r)^4\,{\rm d}r \sim 4\pi r_{\rm in}^2\sigma T_{\rm in}^4. \tag{17}$$

We assume Scenario A with the inner radius $r_{\rm in} = 3R_{\rm sch}$ and the outer radius $r_{\rm out} = 1000R_{\rm sch}$, and according to equation (17), $T_{\rm in} \sim 4.6\times10^6$ K. In addition, we assume the transfer efficiency is $\eta = 50$ per cent and the covering fraction is $R_{\rm c} = 50$ per cent for the hot Dyson sphere while $\eta = 80$ per cent and $R_{\rm c} = 2$ per cent for the solid Dyson sphere. The distance between the black hole and the observer is set at 10 kpc. The resulting hot and solid Dyson sphere spectra of the accretion disc, waste heat, and total flux which we could measure are shown in Fig. 3. In these configurations, the AB magnitude ($m_{\rm AB}$) of the waste heat at 10 nm to 300 nm and 10^3 nm to 10^4 nm are approximately 17 to 20 mag and 18 to 20 mag for the hot and solid Dyson sphere, respectively. The limiting magnitude of Wide Field Camera 3 (WFC3)/UVIS of *Hubble Space Telescope* (*HST*) in NUV(F225W) filter over 1 hour is ∼27 mag[7], suggesting that in this scenario, the hot Dyson sphere could be detected by our current ultraviolet (UV) space telescope. With the *HST*, one can look for these around known black holes/X-ray binaries because the *HST*'s field of view (FoV) is not so large. Alternatively, if one wants to survey a large area, a telescope with a larger FoV would be more suitable such as *Galaxy Evolution Explorer* (*GALEX*) Ultraviolet Sky Surveys, Pan-STARRS1 3π Steradian Survey (optical), VISTA Hemisphere Survey (VHS; near-infrared), Wide-Field Infrared Survey Explorer (*WISE*; mid-infrared), and Sloan Digital Sky Survey (SDSS; optical). These limiting magnitudes are summarized in Table 2 and included in Fig. 3.

If a black hole is closer to us and has a higher mass, the source will be brighter than our scenario ($D = 10$ kpc and $M = 5\,{\rm M}_\odot$). For instance, if the source is at 1 kpc, the AB magnitude of the waste heat at 10 nm to 300 nm and 10^3 nm to 10^4 nm are approximately 12–13 and 13–17 mag of the hot Dyson sphere and the solid Dyson sphere under the same configurations. If the source is under the scenario B ($M = 20\,{\rm M}_\odot$ and Eddington ratio=0.1), the AB magnitude of the waste heat at 10 nm to 100 nm and 10^3 nm to 10^4 nm are approximately 13–15 and 14–18 mag of the hot Dyson sphere and the solid Dyson sphere at 10 kpc.

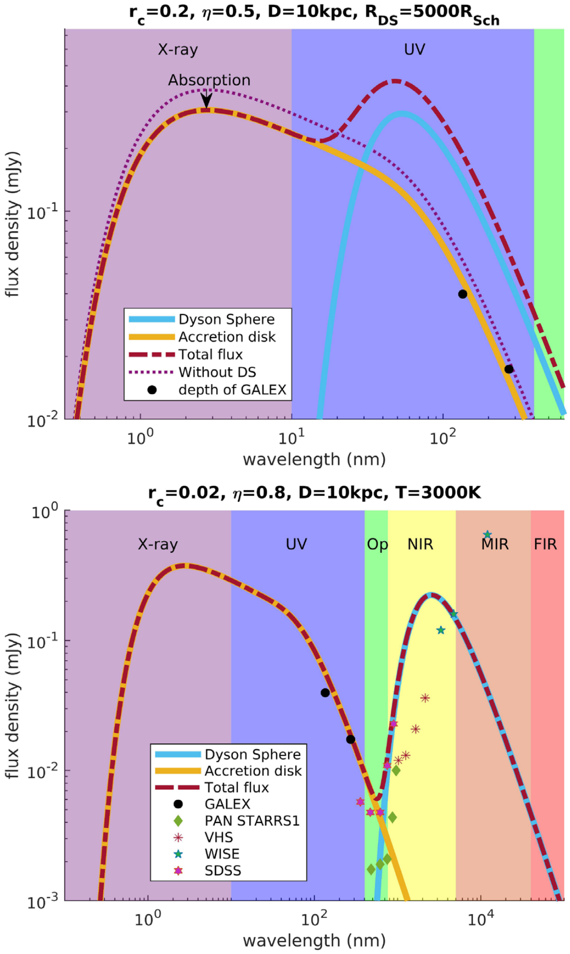

Figure 3. Example spectra of Scenario A ($M = 5\,{\rm M}_\odot$ and $L_{\rm disk} = 1600\,{\rm L}_\odot$). Upper panel: A hot Dyson sphere with covering fraction $R_{\rm c} = 20$ per cent, transfer efficiency $\eta = 50$ per cent , and $R_{\rm DS} = 5000R_{\rm Sch}$. Lower panel: A solid Dyson sphere with covering fraction $R_{\rm c} = 2$ per cent, transfer efficiency $\eta = 80$ per cent, and $R_{\rm DS} = 7.12\times10^6 R_{\rm Sch}$. The yellow curve suggests the accretion disc flux with the absorption of the Dyson sphere [$(1 - R_{\rm c})$ times the original accretion disc flux] while the purple dotted curve is the original flux of accretion disc without surrounding a Dyson sphere. The blue curve shows the flux of the waste heat from the Dyson sphere while the red dotted-line curve indicates the total flux. The black circles, green diamonds, burgundy asterisks, blue stars, and magenta hexagrams indicate the limiting magnitude of *GALEX*, PAN STARRS1, VHS, *WISE*, and SDSS surveys, respectively.

Interestingly, with little algebra ($L_{\rm DS} = R_{\rm c}(1-\eta)L_{\rm disc}$), we derive the temperature of the waste heat, which is not related to the covering fraction:

$$T_{\rm waste} = \left[\frac{(1-\eta)L_{\rm disc}}{4\pi\sigma R_{\rm DS}^2}\right]^{1/4}. \tag{18}$$

In our simulated spectrum, the waste heat of the hot Dyson sphere is $\sim9.5\times10^4$ K. We assume that with the range of $\eta = [0.01, 0.99]$, Eddington ratio = [0.1 per cent, 100 per cent] and radius of the Dyson sphere = $[10^3 R_{\rm Sch}, 10^5 R_{\rm Sch}]$. The possible wavelength (peak wavelength in the blackbody spectrum of the waste heat) to detect a hot Dyson sphere as a function of the black hole mass is

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[7] https://HST-docs.stsci.edu/wfc3ihb/chapter-6-uvis-imaging-with-wfc3/6-8-uvis-sensitivity

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Table 2. Information of the projects.

Project	Band	Exposure time (s)	Limiting magnitude (m_{AB})	Reference
WFC3/UVIS of *HST*	NUV (F225W)	3600 (1 h)	∼27	[a]
GALEX Ultraviolet Sky Surveys	NUV	100	19.9	Bianchi et al. (2011)
	FUV		20.8	
Pan-STARRS1 3π Steradian Survey	g_{P1}	43	23.3	Chambers et al. (2016)
	r_{P1}	40	23.2	
	i_{P1}	35	23.1	
	z_{P1}	30	22.3	
	y_{P1}	30	21.4	
VHS	Y	60	21.2	[b]
	J		21.1	
	H		20.6	
	K_{s}		20.0	
WISE	3.3 µm	8.8	18.7	Mainzer et al. (2005)
	4.7 µm		18.4	
	12 µm		16.9	
	23 µm		15.4	
SDSS	u	53.9	22.0	Abazajian et al. (2004)[c]
	g		22.2	
	r		22.2	
	i		21.3	
	z		20.5	

[a] https://HST-docs.stsci.edu/wfc3ihb/chapter-6-uvis-imaging-with-wfc3/6-8-uvis-sensitivity;
[b] https://people.ast.cam.ac.uk/~rgm/VHS/v4/PS-VHS-v4p2.pdf;
[c] https://www.SDSS.org/dr16/scope/.

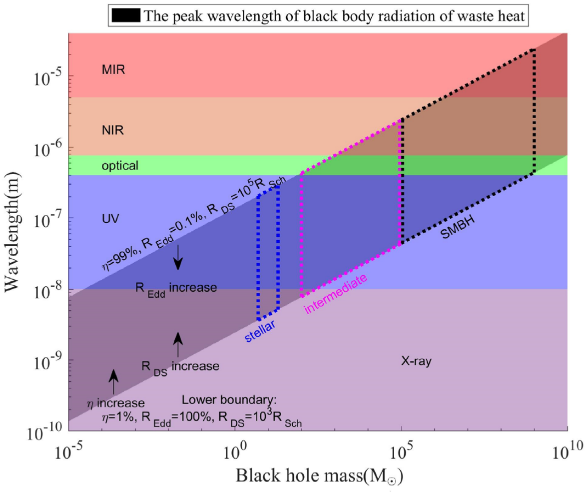

Figure 4. Possible wavelengths for a hot Dyson sphere to be detected in different black hole mass. The purple, blue, green, orange, and red regions indicate X-ray (0.01−10 nm), UV (10−400 nm), optical (400−760 nm), NIR (760 nm−5 µm), and MIR (5−40 µm) wavelengths, respectively. The shaded region is the peak wavelength from blackbody radiation of the waste heat, covering a wide range of parameters of a Dyson sphere. The region enclosed by blue, magenta, and black lines indicate stellar-mass, intermediate-mass, and SMBH. Three arrows show how the peak wavelengths change with increasing parameters. The arrow lengths are arbitrary.

shown in Fig. 4. Our result suggests that the waste heat of a hot Dyson sphere around a black hole is detectable in the UV, optical, near-infrared (NIR), and mid-infrared (MIR) band. We caution readers that star-forming activity and dusty torus would be detected in the longer wavelengths such as IR, which do not disturb the detection of the hot Dyson sphere in the spectrum. However, we caution readers that in our simulation, we assume there is no dust extinction. The waste heat may be severely affected by dust extinction within the Milky Way. Only if the black hole is close to the Earth or is observed in the infrared wavelength, this problem can be avoided. Similarly, a Dyson sphere of more massive black holes are redder, and less affected by the dust extinction. For example, at $M \gtrsim 10^5 - 10^6\,\mathrm{M}_{\odot}$, most emissions from Dyson spheres are in the infrared.

In terms of searching for Dyson spheres around black holes, since Dyson spheres may emit similar temperatures as stars, UV, optical, and infrared sky surveys might be inefficient. We recommend analysing black holes (candidates) in the current catalogue first. If there is spectroscopic data, we can analyse if there are several abnormal peaks. If only photometric data are available, at least we need several band detection such as UV, optical, and infrared to perform spectral energy distribution (SED) fitting (e.g. Hsiao et al. 2020) with the Dyson sphere model spectrum, which will help us to identify the possible Dyson sphere.

There are many factors that may affect the detectability. First of all, if the covering fraction or the transfer efficiency of the Dyson sphere is too small, the feature might be hidden beneath the disc/companion star spectrum. As a result, we may mis-identify them as normal X-ray binaries. In addition, even if the Dyson sphere is bright enough, it may be challenging to distinguish it from a companion star or an exoplanet orbiting around the X-ray binaries (e.g. Imara & Di Stefano 2018). We propose to overcome this problem through model fitting (SED fitting). If the blackbody radiation has an abnormal luminosity with a temperature that cannot be explained by usual models in SED fitting (e.g. star formation histories, etc.), we could further consider the Dyson sphere scenario (e.g. $T = 2000$ K). More robust confirmation comes with a spectrum by checking the absorption lines since low-temperature stars have spectra that have strong molecular bands. If the waste heat of a Dyson sphere has a temperature below ∼2000 K,

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there would be a clear bump in the infrared spectrum that is not expected from a companion star with molecular bands. In addition, if a Dyson sphere collects a huge amount of the energy from the disc, it is possible that the bolometric luminosity is much lower than expected. For example, the spectrum is thermal blackbody radiation but the Eddington ratio is much smaller than 1 per cent, which should be a thick disc and shows a non-thermal feature in the spectra (e.g. Shakura & Sunyaev 1973; Narayan & Yi 1994). This may indicate that the real Eddington ratio is higher but a fraction of the energy is absorbed by a Dyson sphere. Moreover, a Dyson sphere should have a much smaller mass than a companion star or an exoplanet. Operating a telescope to measure the variability of radial velocity will also help distinguishing between companion stars/exoplanets and Dyson spheres candidates.

Inoue & Yokoo (2011) discussed the energy transmitted remotely from a Dyson sphere to a Type II civilization's habitat. In their result, the possibility to detect the transmission of a 1 µas energy beam is less than 10^{-23}. For a stellar-mass black hole, the possibility becomes smaller. A search for these signals from a black hole in the UV, optical, and IR bands is needed to discover the existence of a Type II civilization.

4 CONCLUSION

In this study, we consider an energy source of a well-developed Type II or Type III civilization. They need a more powerful energy source than their own Sun. We discuss and conclude that the collectable energy from the CMB at present by the IDS would be too low ($\sim 10^{15}$ W). Next, the Hawking radiation as a source seems to be rather infeasible since the Hawking luminosity cannot provide adequate energy [e.g. for $5\,\mathrm{M}_\odot$, $L_{\mathrm{Hawking}} \sim 10^{-30}$ W $<< 10^{26}$ W (Type II)].

On the other hand, an accretion disc, a corona, and relativistic jets could be potential power stations for a Type II civilization. Our results suggest that for a stellar-mass black hole, even at a low Eddington ratio, the accretion disc could provide hundreds of times more luminosity than a main-sequence star. If a Type II civilization collects the energy from the accretion disc of an SMBH, the energy could boost the Kardashev index, $K \sim 2.9$. Moreover, the energy reserved in a corona and jets can provide additional energy ($\sim$30 to $\sim$50 per cent for the corona luminosity and $\sim$60 to $\sim$80 per cent for the jets luminosity) aside from the accretion disc. Our results suggest that if a Type II civilization collects the energy from jets and electromagnetic radiation simultaneously, for an SMBH with a mass similar to Sgr A$*$, the Kardashev index can reach $\sim$3. Overall, a black hole can be a promising source and is more efficient than harvesting from a main-sequence star.

We also discuss a possible location of a Dyson sphere around a black hole. To absorb the accretion disc luminosity, a Dyson ring or a Dyson Swarm could be a possible structure. A Dyson sphere should be located outside of the accretion disc, $\sim 10^3 R_{\mathrm{sch}}$–$10^5 R_{\mathrm{sch}}$. However, in this region, the hot temperature would melt the solid structure. In order to avoid melting of the solid Dyson sphere, the solid Dyson sphere ($T = 3000$ K) should be located at $R_{\mathrm{DS}} \gtrsim 10^7 R_{\mathrm{Sch}}$ and $R_{\mathrm{DS}} \gtrsim 10^3 R_{\mathrm{Sch}}$ for a stellar-mass black hole and an SMBH, respectively. The size of an accretion disc for a stellar-mass black hole is smaller than the size of the Sun, which means that a Dyson sphere around the stellar-mass black hole can be smaller than that around the Sun. In terms of relativistic jets, a possible form of a Dyson sphere is a Dyson Bubble. Balancing the pressure and the gravity from the black hole, a light sail could be stationary in space and can continuously collect the energy from the jets. Light sails also absorb the luminosity from the accretion disc at the same time. Our results suggest that the best way to place a light sail is close to the origin of the jets, which could save the materials to build a light sail.

Moreover, a hot Dyson sphere around a stellar-mass black hole in the Milky Way (10 kpc away from us) is detectable in the UV (10−400 nm), optical (400−760 nm), NIR (760 nm−5 µm), and MIR (5−40 µm), which can be detected by our current telescopes (e.g. WFC3/*HST* and *GALEX* survey). For a solid Dyson sphere, the limiting magnitude of the sky surveys such as Pan STARRS1, VHS, *WISE*, and SDSS are smaller than the flux density from the solid Dyson sphere, which indicates that the solid Dyson sphere is bright enough to be detected. In addition, the presence of Dyson spheres may be imprinted in spectra. Performing model fitting and measuring the radial velocity will help us to identify these possible artificial structures.

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DATA AVAILABILITY

The data underlying this article will be shared on reasonable request to the corresponding author.

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