Exploration of M31 via Black-Hole Slingshots and the “Intergalactic Imperative”

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ABSTRACT

I show that a gravitational slingshot using a stellar-mass black hole (BH) orbiting SgrA* could launch robotic spacecraft toward M31 at $0.1\,c$, a speed that is ultimately limited by the tensile strength of steel and the BH mass, here conservatively estimated as $m_{\text{bh}} = 5\,M_\odot$. The BH encounter must be accurate to $\lesssim 1\,\text{km}$, despite the fact that the BH is dark. Navigation guided by gravitational microlensing can easily achieve this. Deceleration into M31 would rely on a similar engagement (but in reverse) with an orbiting BH near the M31 center. Similarly for a return trip, if necessary. Colonization of M31 planets on 50 Myr timescales is therefore feasible provided that reconstruction of humans, transhumans, or androids from digital data becomes feasible in the next few Myr. The implications for Fermi’s Paradox (FP) are discussed. FP is restated in a more challenging form. The possibility of intergalactic colonization on timescales much shorter than the age of Earth significantly tightens FP. It can thereby impact our approach to astrobiology on few-decade timescales. I suggest using a network of tight white-dwarf-binary “hubs” as the backbone of a $0.002\,c$ intra-Galactic transport system, which would enable complete exploration of the Milky Way (hence full measurement of all non-zero terms in the Drake equation) on 10 Myr timescales. Such a survey would reveal the reality and/or severity of an “intergalactic imperative”.

Subject headings: gravitational lensing, micro, astrobiology, black hole physics, space vehicles, celestial mechanics, Galaxy: center, Local Group

1. Introduction

At first sight, the problem of exploring and colonizing other galaxies does not appear to be very pressing. Even with near-$c$ travel, it would take 2.5 Myr for a probe to reach the
nearest large galaxy (M31), and another 2.5 Myr to receive any report on what it discovered. The problems of launching toward (not to speak of then stopping upon arrival at) M31 appear to be orders or magnitude more difficult than sending probes to planets of the nearest stars, which itself is a daunting enterprise. Hence, the problem of intergalactic exploration and colonization seems little more than an intellectual pastime.

Nevertheless, such “impractical” intellectual exercises can have quite practical effects, both in stimulating ideas to achieve more prosaic aims and in framing our perspective on how to focus present resources.

Here, I demonstrate a “practical” method of launching a space probe toward M31 at $0.1c$ using a black-hole (BH) slingshot. The same mechanism could be used to stop the probe in M31 and then relaunch it back to the Milky Way (MW) after it had carried out its explorations. The method is “practical” in the sense that it does not violate any laws of physics, relies on our present understanding of materials science, and does not require exorbitant resources.

2. Slingshot Mechanism

The slingshot mechanism has been used for decades to assist in the launching of probes into the outer solar system. For example, the Pioneer 10 & 11 and Voyager 1 & 2 missions (launched 1972–1977) all used an assist from Jupiter to reach (and then leave) the outer solar system. The idea is simple. By conservation of energy, the satellite must enter and leave the gravitational influence of Jupiter at the same speed as seen from the Jupiter frame: only the direction is changed by the encounter with Jupiter. However, Jupiter is moving in the solar frame. If the angle of the outgoing spacecraft motion is more aligned to Jupiter’s own motion than the angle of the incoming motion, then the velocity of the spacecraft will increase in the solar frame.

The same principle can be applied to any orbiting body, and indeed reapplied repeatedly. For example, NASA was able to launch (in 1989) the very heavy Galileo probe to Jupiter by making use of four slingshot maneuvers, first at Venus, then at Earth, then at Gaspra, then at Earth again.

3. Tidal Limit

One problem that NASA has not so far encountered in applying the slingshot method is tidal disruption of the spacecraft. Tidal acceleration is basically given by the mean density
interior to the orbit, and the greatest such interior density within the solar system would occur in a near passage to Earth\(^1\). However, this tidal acceleration would be the same as sitting on Earth. So, if the spacecraft could be constructed on Earth, then it would easily survive such tidal stresses.

Nevertheless, for BH slingshots, tidal stress will prove to be the limiting factor. Consider a spacecraft in the shape of a cube of size \(\ell\), whose walls have thickness \(t \ll \ell\) and composed of material of density \(\rho\). When the center of the cube is at a distance \(r\) from a BH of mass \(m\), the near and far walls of the cube will each suffer equal and opposite tidal forces of

\[
F = (2Gm/r^3)(\ell^2 t \rho)(\ell/2) = (Gm/r^3)\rho \ell^3 t.
\]

This tidal force will have to be supported by walls with total area \(A = 4\ell t\). Hence, the two faces alone require support of \(F/A = (Gm/r^3)\rho \ell^2 / 4\). The four walls themselves must also be supported. These have two times larger mass but only 1/3 the mean tidal acceleration. Hence, \(F/A = (5/12)(Gm/r^3)\rho \ell^2\). Finally, the spacecraft should have some content (not just walls). I parameterize this by \(F/A = \zeta(Gm/r^3)\rho \ell^2\), where \(\zeta\) is of order 1 or 2. I evaluate this in a way that can be related to material properties,

\[
\frac{F/A}{\rho} = \frac{Gm}{r^3} \ell^2 = \frac{Gm}{r_g} \left(\frac{\ell}{r_g}\right)^2 \frac{1}{n^3} = \zeta \left(\frac{\ell}{r_g}\right)^2 \frac{c^2}{n^3},
\]

where \(r_g\) is the gravitational radius of the BH, and \(r = nr_g\) is the spacecraft’s distance from the BH.

We can now equate this to

\[
V_{\text{steel}}^2 = \frac{T_{\text{steel}}}{\rho_{\text{steel}}} = \frac{2.53 \text{ GPa}}{8 \text{ gm/cm}^3} = (0.56 \text{ km s}^{-1})^2 = 3.5 \times 10^{-12} c^2
\]

where \(T_{\text{steel}}\) is the tensile strength of steel, \(\rho_{\text{steel}}\) is its density and GPa= 10\(^9\) newtons/m\(^2\). Equating \(T\) with \(F/A\) yields

\[
n = \left(\sqrt{\zeta} \frac{\ell}{r_g} \frac{c}{V_{\text{steel}}}\right)^{2/3} = 80 \zeta^{1/3} \left(\frac{r_g/\ell}{750}\right)^{-2/3},
\]

where I have normalized the evaluation to an \(\ell = 10\) m box passing by an \(m = 5 M_\odot\) \((r_g = 7.5\) km\) BH. We see that the result depends only weakly on \(\zeta\). Before, proceeding, I note that \(V_{\text{steel}}\) is well below the speed of sound in steel, which is roughly 3 km s\(^{-1}\).

4. Black-hole Slingshot Mechanism

I consider a small black hole (BH) of mass \(m\) in a circular orbit at \(N\) gravitational radii of a larger BH of mass \(M \gg m\), where \(N \gg 1\), i.e., at velocity \(v = c/\sqrt{N}\).

\(^1\)In principle, very close passage to a metallic (iron) asteroid could produce slightly higher tidal forces.
I now calculate the orbit of a test particle that “falls” from infinity, and passes the smaller BH at peribothron \( q_{bh} \) of \( n \) gravitational radii (of the smaller BH). However, rather than directly “falling”, i.e., on a radial orbit, I will consider the more general case that the test particle has some angular momentum so that its trajectory intersects that of the small BH at an arbitrary angle \( \phi \) as seen in the frame of the large BH.

Normally, the Rutherford scattering angle is written, 
\[
\psi = 2 \tan^{-1} \frac{Gm}{v_0^2 b},
\]
where \( b \) is the impact parameter and \( v_0 \) is the velocity at “infinity” (i.e., away from the potential of the central mass). However, in our case, the controlling variables are \( v_0 \) and \( q_{bh} \) (the peribothron), the first being set by the geometry of the problem and the second by the tidal constraints from Section 3. By imposing energy and momentum conservation, we obtain 
\[
b = q \sqrt{1 + 2/\xi},
\]
and so Equation (4) becomes
\[
\psi = 2 \cot^{-1} \left( \xi \sqrt{1 + \frac{2}{\xi}} \right) = 2 \csc^{-1}(1 + \xi); \quad \xi \equiv \frac{v_0^2 q_{bh}}{Gm} \rightarrow n \frac{v_0^2}{c^2},
\]
or
\[
\cos \psi = 1 - \frac{2}{(1 + \xi)^2}; \quad \sin \psi \rightarrow \frac{2}{1 + \xi} - \frac{1}{(1 + \xi)^3} - \frac{1}{4(1 + \xi)^5} \cdots
\]

In the frame of the small BH, the test particle will have incoming velocity \( v_0 = (1 - \sqrt{2} \cos \phi, \sqrt{2} \sin \phi)c/\sqrt{N} \), i.e., \( v_0/c = \eta/\sqrt{N} \), and at angle \( \delta \) defined by 
\[
\cos \delta = (\sqrt{2} \cos \phi - 1)/\eta, \quad \sin \delta = \sqrt{2} \sin \phi/\eta,
\]
with \( \eta^2 \equiv (3 - \sqrt{8} \cos \phi) \). Hence, \( \xi = \eta^2 n/N \). Then, by the law of cosines, the exit speed squared (in the large-BH frame) is,
\[
\frac{v_1^2}{c^2} = \frac{\eta^2 + 1}{N} - 2 \frac{\eta}{N} \cos(\psi + \delta),
\]
and hence it will escape to infinity at speed
\[
\frac{v_2^2}{c^2} = \frac{\eta^2 - 1}{N} - 2 \frac{\eta}{N} \cos(\psi + \delta) = \frac{1}{N} \left( 2 - \sqrt{8} \cos(\phi - 2(1 - \frac{2}{(1 + \xi)^2}))(1 - \sqrt{2} \cos \phi) + \sqrt{8} \sin \phi \sin \psi \right)
\]
\[
= \frac{1}{N} \left( \frac{4(1 - \sqrt{2} \cos \phi)}{(1 + \xi)^2} + \sqrt{8} \sin \phi \sin \psi \right).
\]
Figure 4 illustrates Equation (10) for various values of \( N/n \).

To gain analytic insight, I now consider the special case of \( \phi = 90^\circ \), i.e., that the test particle is initially falling directly into the large-BH potential. Then, \( \xi \rightarrow 3n/N \), and Equation (10) becomes,
\[
\frac{v_2^2}{c^2} = \frac{4/(1 + \xi)^2 + \sqrt{8} \sin \psi}{N} = \frac{\sqrt{32}}{N + 3n} + \frac{4N}{(N + 3n)^2} - \frac{\sqrt{8}N^2}{(N + 3n)^3} + O \left( \frac{N}{N + 3n} \right)^5.
\]
The derivative of the first two terms with respect to \( N \) is strictly negative, and I have confirmed that the exact expression falls monotonically with \( N \) for \( n \gg 1 \). Hence, for fixed \( n \), the maximum ejection speed is approached for any value \( N < n \). For example, for \( N = n \) \((\xi = 3, \sin \psi = 0.176)\), the ejection speed is already 86% of the maximum possible,

\[
v_{2,\text{max}} = \left(\frac{32}{9}\right)^{1/4} \frac{c}{\sqrt{n}},
\]

where \( n \) is the closest allowed peribothron, which is set by the physical properties of the spacecraft and the mass \( m \) of the smaller BH.

Combining this with the estimate \( n \sim 100 \) from Section 3, we obtain \( v_{\text{final}} \sim [(32/9)^{1/4}/\sqrt{100}]c = 0.14c \). More conservatively, I adopt \( v_{\text{final}} \sim 0.1c \) as feasible.

Of course, it would not be possible to launch toward M31 at Galactic coordinates \((l, b) = (+121.2, -21.5)\) via slingshot from a small BH in a circular orbit from a strictly radial spacecraft orbit. However, one could roughly reverse the geometry simply by sending the spacecraft into a nearby encounter with the supermassive BH and arranging the encounter with the small BH on the return. In the extreme limit, this would reduce the required deflection from 120° to 60°. With a less extreme approach to the supermassive BH, the required deflection angle could be further reduced.

I do not pursue this issue in detail because the real population of small BHs will not be on circular orbits, and moreover, the parameters of these orbits (at the time of the encounter) will be completely unknown at the time the mission takes off from the solar system. The real problem will therefore be precision mapping of the orbits (and masses) of this population and then choosing the best small BH for the slingshot. I now turn to this problem.

5. Mapping the BH Population at the Galactic Center

BHs do not emit radiation and so are, per se, “invisible”. While in principle they do emit Hawking (1975) radiation, the temperature of an \( M \sim 5 M_\odot \) BH is \( \sim 10^{-8} \) smaller than that of the cosmic microwave background (CMB). Hence, what could be seen, in principle, is a “hole” in the CMB. However, resolving this hole from an observatory in the solar system would require an apparatus with dimension \( D \sim (\lambda/r_g)R_0 \sim 200 \text{ au} \), with sufficient collecting area to make an image during the BH \( r_g \) self-crossing time, roughly 1 ms. Here, \( \lambda \) is the radiation wavelength and \( R_0 \) is the Galactocentric distance. One could imagine looking for the “hole” in \( K \)-band light from some background source (such as SgrA*), which would reduce the dimensions of the apparatus by a factor 500, but would still require a huge collecting area for the 1 ms imaging against high-background.
Without placing doubts on the capabilities of our descendants, I think that the prospects for such projects are remote. However, from the current standpoint, the main issue is not their practicality, but their utility for planning a slingshot mission. The BH orbital parameters are not needed at the time of launch from Earth, but rather several Myr later at the time of the slingshot boost. Of order a billion BH orbits will elapse during this interval. As we will see, the 3-space position of the BH must be predicted to of order 1 km. Hence, even a thorough mapping of the Galactic center from Earth would be of little use in preparing a slingshot. On the other hand, using the technique of gravitational microlensing (Einstein 1936), it is quite feasible to obtain a detailed map of the BH distribution as the spacecraft approaches the Galactic center. In this context, constraints on the overall small-BH population that is orbiting SgrA* would be important to planning the mission, and this could be achieved with a combination of microlensing and gravitational wave observations. However, the details of such an investigation lie beyond the scope of the present work.

5.1. Microlensing Basics

For present purposes, the main required microlensing concepts are the angular Einstein radius, $\theta_E$, and the Einstein timescale, $t_E$,

$$
\theta_E = \sqrt{\kappa M_L \pi_{\text{rel}}}; \quad t_E = \frac{\theta_E}{\mu_{\text{rel}}}; \quad \kappa = \frac{4G}{c^2 \text{au}} \approx 8.14 \text{ mas} \quad \frac{M}{M_\odot},
$$

where $M_L$ is the lens mass and $(\pi_{\text{rel}}, \mu_{\text{rel}})$ are the lens-source relative (parallax, proper motion). If the lens-source angular separation (normalized to $\theta_E$) is $u$, then the lens will split the source light into two images, one outside the “Einstein ring” on the same side as the source, and one inside the Einstein ring, on the opposite side, with positions and magnifications

$$
\theta_\pm = \theta_L + \frac{u \pm \sqrt{u^2 + 4}}{2} \theta_E; \quad A_\pm = \frac{A \pm 1}{2}; \quad A = \frac{u^2 + 2}{u \sqrt{u^2 + 4}}.
$$

The key points about these equations are first, that $A \to 1/u$ and $A \to 1 + 2/u^4$ for $u \ll 1$ and $u \gg 1$, respectively. Hence, the magnification can be significant only when the source is inside or near the Einstein ring. And second, for the first limit the images are of about equal brightness and both are close to the Einstein ring, while in the second limit, the major image is close to the source position, while the minor image is highly demagnified, $A_- \to u^{-4}$.

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2J. Carpenter was the first to suggest that gravitational lensing could play a key role in travel to M31, but he did not present any details (“They Live”, 1988).
5.2. BH Mapping from Earth: Microlensing Blind spot

The small-BH population that very likely orbits SgrA* (Gould & Miralda-Escude 2000) cannot be mapped by microlensing observations from Earth. There is a general problem that the probability that any given BH is magnifying a background star is very low, so that successive microlensing events, likely separated by thousands of years, cannot be distinguished from other events due to other BHs. But there is also a more fundamental problem. For a source star with relative lens-source distance $D_{LS} = D_S - D_L \ll D_L$, the physical Einstein radius $r_E = D_L \theta_E$ due to SgrA* itself is well approximated by,

$$r_{E,SgrA*} \approx 180 \text{ au} \frac{D_{LS}}{1 \text{ pc}} = 4500 r_{g,SgrA*} \frac{D_{LS}}{1 \text{ pc}}.$$  \hspace{1cm} (14)

Imaging by additional lenses (such as the small BHs that orbit SgrA*) that lie well outside this radius are not qualitatively affected by SgrA* lensing. For small BHs that are projected exactly on, or very close to $r_{E,SgrA*}$, detection is quite feasible and has interesting features. Mathematically, this is the regime of resonant caustics in “planetary microlensing”. I discuss this regime in Section 5.4. However, small BHs that lie well within this radius very rarely leave any detectable microlensing signature. Thus, the small BHs that are detectable from Earth, with orbital velocities $v/c < (4500)^{-1/2} \sim 0.015$ are not relevant to the slingshot mechanism. That is, such boosts are only halfway (in log) between what can actually be achieved and what could be achieved by slingshots from local white-dwarf (WD) binaries, without going to the Galactic center, as I discuss in Section 7.

5.3. In-Flight BH Mapping

The blind spot will only begin to substantially contract relative to Equation (14) when the spacecraft comes within 1 pc of SgrA*. At this point, we can also begin to consider the general populations of bulge sources, which are both much more distant, $D_S \sim 1$ kpc, and much more numerous than those in the nuclear star cluster. In this regime, the formula is similar to Equation (14), but with $D_{LS} \rightarrow D_L$.

$$r_{E,SgrA*} \sim 180 \text{ au} \frac{D_L}{1 \text{ pc}} = 4500 r_{g,SgrA*} \frac{D_L}{1 \text{ pc}}.$$  \hspace{1cm} (15)

Hence, the innermost relevant BHs will begin to “come into focus” at about $D_L \sim 100$ au, which corresponds to two weeks prior to slingshot (when the infalling speed is already 0.03 $c$).

I analyze the observations required to measure the BH masses and orbits within the framework of isolated small-BH lenses. In fact, when the small-BH first comes into focus,
it will act like a “microlensing planet” from the standpoint of the microlensing formalism. That is, the positions and magnifications of the microlensed images can only be understood as a product of the combined influence of the small-BH “planet” and its SgrA* “host”. Their mass ratio, $q \sim 10^{-6}$, happens to be just below that of the most extreme current detections (Gould et al. 2020; Yee et al. 2021; Zang et al. 2021a,b). Nevertheless, from the standpoint of understanding the basic principles, it is best to begin with the simpler case. I will then take account of “planetary” microlensing in Section 5.4. Moreover, the case of isolated small-BH microlensing becomes increasingly relevant as the spacecraft approaches slingshot.

At these epochs (when $D_L < 100$ au), the small-BH angular Einstein radius and Einstein timescale would be

$$\theta_E = 9'' \left( \frac{D_L}{100 \text{ au}} \right)^{-1/2}; \quad t_E = 20 \text{ s} \left( \frac{D_L}{100 \text{ au}} \right)^{1/2};$$  \hspace{1cm} (16)$$

where I have assumed that the small BH is moving at $0.1 c$ across the line of sight. The main population of sources will be the Galactic bulge dwarf stars, with a characteristic distance of $D_S \sim 1$ kpc, and with a surface density for a very conservatively chosen $M_K < 4$ (i.e., $K_0 < 14$, and so $K < 16$ allowing for $A_K = 2$) of $N_{K < 16} \sim 0.05 \text{ arcsec}^{-2}$. Hence, at any given moment, there would be of order 12 stars inside the Einstein ring, including of order 3 that were magnified by at least a factor 2 (so with counter-image $A_\sim = (A - 1)/2 \geq 0.5$, at least half as bright as the source). The main potential problem is that the lens is moving relative to the source at about $2''/s$ (and the magnified images can be moving even faster), so that exposure times should be kept to e.g., 0.1 s. However, it is not necessary that the individual images have high signal-to-noise ratio (SNR) to reconstruct the lensed-image brightness and trajectory from a high-cadence series of observations. Thus, effectively, the integrated SNR would be that of a 20 s exposure of a $K \sim 16$ star, which would yield very precise results even with a small (e.g., 2m) telescope.

As noted above, the “final descent” toward SgrA* would take about 2 weeks. During this time, there would be a near continuous series of such measurements, with repeated, but ever shorter interruptions as the lens passed through the SgrA* blind spot. These observations would cover about 10 orbits and would comprise about about $6 \times 10^4$ individual epochs.

I now examine what is learned from each observation and how the information from these observations can be combined to determine the BH orbit to high precision. I will argue below that the required precision is $\sim 1$ km, including, in particular, the distance between the spacecraft and the BH along the line of sight.

Each “observation” is actually a track of observations as the images streak across the Einstein ring. Nevertheless, from the standpoint of understanding the basic physics, I treat these observations as though they were a single observation at the impact parameter $u_0$. 


In fact, there will be somewhat more information than is accounted for in this simplified presentation.

The first point is that each observation, by itself, gives a measurement of $\theta_E$ from the offset of the two images. From Equation (13),

$$\theta_E = \frac{\theta_+ - \theta_-}{\sqrt{4 + u_0^2}} = \frac{\theta_+ - \theta_-}{\sqrt{2 + 2/\sqrt{1 - 1/A^2}}} \quad (17)$$

The total magnification at peak (or equivalently $u_0$) can be determined, as usual, from fitting the microlensing event. However, in contrast to current microlensing experiments, the probability of there being blended light within the point-spread function (PSF) that does not participate in the event is very low because the Einstein radius is much larger than the PSF. In any case, the magnification can be determined from the flux ratio $r = F_-/F_+$ of the two images, $A = (1 + r)/(1 - r)$. And the three methods can be cross checked for consistency.

The lens position can be derived from the mean position of the two images.

$$\theta_L = \frac{\theta_+ + \theta_-}{2} - u_0 \theta_E, \quad (18)$$

where $\theta_E$ can be determined from Equation (17) and, again, $u_0$ can be derived from $A$ or $r = F_-/F_+$. Then, adopting a total SNR = 100 and 0.25\arcsec FWHM, each measurement would yield a measurement of $\theta_E$ with fractional precision $10^{-5}$ and a lens angular-position measurement with precision of order 1 mas. The latter corresponds to about 75 km from 100 AU. While this is substantially larger than 1 km, the combined information from $3 \times 10^5$ measurements ($6 \times 10^4$ epochs, each with $\sim 5$ background stars), constrained by the Kepler equations of the small-BH orbit, would satisfy this requirement. Note that a series of 2-dimensional position measurements alone (combined with the orbital equation) are sufficient to solve for the orbital parameters (up to a sign flip in the orientation of the orbit).

The interpretation of these measurements requires first that they be placed on an absolute angular coordinate system, and second that the distance $D_L$ be known at high precision (to convert angular measurements made at many different distances into a common physical system).

The first is easily achieved via the Einstein ring of SgrA*. This will be delineated with excellent precision in every image by the tens of thousands of highly magnified $A > 100$ images lying within 10\arcsec of the 2.5\degree Einstein radius of SgrA*. These include also the much more numerous $M_K \lesssim 8$ sources that are magnified into view. Hence both the position and Einstein radius of SgrA* can be determined in the same way as that of the small BH, but more precisely.
Strictly speaking the Einstein radius is a function not only of the mass and distance to the lens, but also the distance to the source, \( \theta^2_E = \kappa M\pi_{\text{rel}} \propto (M/D_L)(1 - D_L/D_S) \). However, the last term is extremely small, \( D_L/D_S \sim 100 \text{ au}/1 \text{ kpc} \sim 10^{-6} \) and, in addition, the individual distances to sources would be known quite well from millenia of astrometric observations of the field as the spacecraft approached SgrA*. So, for purposes of discussion, I just replace \( \pi_{\text{rel}} \rightarrow \pi_L = \text{au}/D_L \).

Then, for any given observation, the BH mass ratio \( q = m/M \) is given by

\[
q = \frac{\theta^2_{E,\text{small-BH}}}{\theta^2_{E,\text{SgrA*}}} \frac{D_{\text{SgrA*}}}{D_{\text{small-BH}}}.
\]  

(19)

Note that while, in the context of Earth-bound planetary microlensing, the distance ratio in the last term is unity to high precision, it can differ significantly in the present case. This is due both to the fact that the small BH is moving closer and farther in its orbit and also because they are viewed at different angles. Nevertheless, this ratio is known from the overall geometry of the system. As the mass of SgrA* is already known today to 0.3% precision, \( M_{\text{SgrA*}} = 4.154 \pm 0.014 \times 10^6 M_\odot \) (GRAVITY Collaboration 2019), and this is still improving using current instruments, the small-BH mass would also be known to extremely high precision. Moreover, each image, with its concomitant measurement of the angular Einstein radius of SgrA*, will give a precise determination of \( D_{\text{SgrA*}} \).

As mentioned above, the orbit of the small BH can be solved from a series of 2-D measurements (up to a sign flip in the plane of the sky). This degeneracy is easily resolved because \( \theta_{E,\text{small-BH}} \) will be larger when the small BH is on the near side of the plane defined by SgrA*.

5.4. Effects of “Planetary Microlensing”, etc.

In fact, there will be many effects that are not captured by the simple approximations of the previous section. I list the principal ones here. However, the main point is that they are all deterministic and well understood. Hence, while they require more complex calculations than those described above, they do not in any way modify the feasibility of the approach.

Overall, the main modification is that the observations will almost all be in the regime of “wide planetary microlensing”, i.e., \( s > 1 \), where \( s \) is the separation between SgrA* and the small BH in units of Einstein radius of SgrA*. (For a review of planetary microlensing, see Gaudi 2012.) For example, the magnification pattern generated by the small BH, will not be according to the simple, axisymmetric formulae of Equation (13). Rather, in the presence of the larger-mass “host”, it is characterized by a quadrilateral caustic structure.
of width (in units of the SgrA* Einstein radius) \( w \sim 2q^{1/2}/s^2 \) (see Equations (6) and (7) of Han 2006 for more precise estimates). This corresponds to \( w_p = w/q^{1/2} = 2/s^2 \) in units of the small-BH Einstein radius (where \( s \) is still in units of the large-BH Einstein radius).

Hence, the formalism of the previous section would only approximately apply at \( s \gtrsim 4 \). For example, for \( s = 2 \), \( w_p = 0.5 \). So, for the simple well-magnified \((u_0 = 0.5)\) example described in the previous section, the source magnification and position would be significantly affected by the four “magnification ridgelines” extending from the cusps of the caustic. And, for about half of such events (i.e., \( u_0 < 0.25 \)), the two images would suddenly be joined by two additional images as the source crossed the caustic. These would appear as a highly magnified pairs on opposite sides of the “critical curve” (the mapping of the caustic onto the image plane) whenever the source was just inside the caustic, and they would disappear when the source again crossed to go outside the caustic. Hence, the mathematics of determining the lens position would be very different from that outlined in the previous section, but would still be unambiguous.

Another effect, which is generally not faced in planetary microlensing is that “host” and “planet” could not be safely approximated as lying in the plane of the sky because the difference in their distances might be of order 1% or more. Nevertheless, it is straightforward to take account of this using standard ray-tracing techniques. Finally, microlensing calculations almost always assume non-relativistic motion. In fact, at the \( \sim 0.1c \) velocities being considered here, this approximation is quite good, but probably not good enough for the 1 km (i.e., 0.1%) precision envisaged. Nevertheless, even the fully relativistic problem is well-understood today (Zheng & Gould 2000).

6. Shepherd Spacecraft

While the microlensed image observations described in Section 5.3 would identify all BHs in the neighborhood of SgrA*, and also yield very precise measurements of their masses and orbits, they might not take place soon enough to enable the spacecraft to make in-flight maneuvers to be properly “launched” toward M31 by BH slingshot. That is, the observations only become possible very late, when the small-BHs move out of the SgrA* blind spot. See Sections 5.2 and 5.3.

This problem can easily be solved by having a second (“shepherd”) spacecraft, which serves to guide the primary spacecraft toward its launch site. The shepherd spacecraft would travel a few hundred au in front. It would make a map of all the small BHs and choose the best one for the launch. Then, it would radio this information back to the primary spacecraft.
After carrying out this mission, the shepherd spacecraft could plunge deep into the
potential well of SgrA*, which would enable it to head back toward Earth. On its return,
it could receive a report from the primary spacecraft summarizing the success (or other-
wise) of its launch. Then it could convey this message to Earth when it reached the solar
neighborhood, a few Myr later.

7. Sketch of a Journey

As far as we are currently aware, the closest supermassive BH is SgrA*, at the Galactic
center, roughly 8 kpc from Earth. Assuming that the spacecraft were constructed on or near
Earth, it would have to first be transported to the Galactic center before being launched
toward M31. Because M31 is 100 times farther than SgrA*, the spacecraft should not travel
much slower than 3% of the speed of its intergalactic voyage, i.e., $v_{\text{local}} \gtrsim 0.003 \, c$, so as not to
contribute substantially to the total time. It is quite possible that during the several thousand
years before such a spacecraft is constructed, the means will be developed to achieve such
launch speeds from Earth (or its environs). However, here I point out that a sling-shot boost
from a white-dwarf (WD) binary could yield a velocity of this order. For example, a binary
composed of two $0.6 \, M_\odot$ WDs of radius $R_{\text{WD}} \sim 10,000 \, \text{km}$ and separated by $a = j \, R_{\text{WD}}$
would have an internal velocity (relative to the center of mass) of $v = 2000 \, j^{-1/2} \, \text{km s}^{-1}$.

The merger time from gravitational-wave emission for such a system is,

$$\Delta t_{\text{merge}} = \frac{5}{512} \left( \frac{ac^2}{GM_{\text{WD}}} \right)^{3/2} \frac{3}{c} \sim 0.15 \left( \frac{j}{10} \right)^4 \, \text{Myr}. \quad (20)$$

The travel time from Earth to this “booster system” can be somewhat longer than the merger
time, but not dramatically longer; otherwise small errors in the prediction of its evolution
would be catastrophic. These times would be equal for $j = 10$, a booster-system distance of
30 pc, and an initial velocity of $200 \, \text{km s}^{-1}$. The separation $j = 10$ corresponds to internal
velocities of $v \sim 600 \, \text{km s}^{-1} = 0.002 \, c$. Note that the tidal forces experienced in such an
encounter would be substantially smaller than those of its final launch from the Galactic
center.

Navigation would require some fuel, particularly for fine steering toward the encounter
with the local WD binary, and then toward the small-BH in preparation for slingshot launch
toward M31. However, overall fuel consumption could be minimized by utilizing two effects.
First, very small changes in the angle of the trajectory could be made by deflection off the
interstellar medium. Second, in the dense environment of the Galactic center, major deflec-
tions would be possible from gravitational encounters with BHs (before or after encountering
the main slingshot BH). I have calibrated my calculations to the requirement of 1 km (∼ 0.1) precision encounter with the small BH, which could potentially lead to a $10^{-3}$ radian error in the angle of approach to M31. It seems plausible that such small corrections could be achieved in the dense environment of the Galactic center. However, if not, these calculations showed that the SNR of the microlensing measurements would permit encounters that are an order of magnitude more precise.

Once arriving at M31, it would be necessary to slow down in order to explore that galaxy. This could be achieved by applying the inverse process to the small BHs orbiting the $M_{M31-BH} \sim 3 \times 10^7 M_\odot$ supermassive BH at M31’s center. The problem of navigating the approach to this “anti-slingshot” event would be more challenging than the MW slingshot in the sense that the approach speed (at the time that the blind spot became small enough to map the small-BH distribution) would be $0.1c$, rather than $0.03c$. However, these difficulties would be significantly ameliorated by the fact that the M31-center BH is larger by a factor $M_{M31-BH}/M_{SgrA*} \sim 7$. Hence, for fixed orbital velocity of a small BH, its semi-major axis would be 7 times larger, meaning that this orbit would start “coming into focus” at a distance that is $\sqrt{7} \sim 2.6$ times larger than in the case of the MW. Thus, these two factors roughly cancel, meaning that the overall level of difficulty will be similar. Thus, it will be essential for the spacecraft to launch a daughter probe that would map the M31 BH system in advance of its own arrival, similar to the “shepherd” spacecraft described in Section 6 for the encounter near Sgr A*.

After slowing to a reasonable velocity, several courses of action could be pursued, depending on the level of technological development. At the low-end, the spacecraft could navigate around M31 using WD binaries, and make flybys of planetary systems that had been identified from Earth. At a higher end, it could land on a planet and then use local materials plus stored DNA sequences, possibly mixed with computer/robot designs to begin colonizing that planet. After this colony was established, it could serve as the center of a colonization system of many M31 planets. These colonies might be able to send electromagnetic signals back to Earth. But even if not, they could launch a similar slingshot back to Earth using the M31-center BH. In this case, it would be unnecessary to go through SgrA*, because the information learned from M31 could be communicated in a $0.1c$ Earth flyby. Similarly, for the case that the spacecraft never landed, but simply explored, it could return toward Earth via an M31-center slingshot.

Assuming $0.1c$ intra Local-Group travel, the whole mission would take about 70 Myr, plus an optional 25 Myr to return to Earth. See Table 1.
8. Proof of Principle and Competing Approaches

The main point of this paper is to demonstrate that travel by robotic spacecraft to M31 on timescales that are short compared to the age of Earth (though long compared to the time of human divergence from apes) is feasible. Further, colonization by human, trans-human, or android beings is plausibly feasible, although this would rest on still-to-be-developed technology of digital-based reconstruction of such beings. Before addressing the implications of these feasibility arguments, I first acknowledge that M31 exploration may well be carried out using some other technology. I present one other example here, including both its advantages and drawbacks. However, this is really just for illustration. Whether slingshots are used, or some other approach, the conclusion remains that intergalactic exploration is feasible on 70 Myr timescales, or perhaps shorter.

Another method would be to launch (somehow, see below) a spacecraft directly toward M31 that accelerated for some time $\Delta t$ at, e.g., 1 $g$, and then decelerated for a similar duration as it approached arrival. I parameterize $\beta = \tanh \Theta$, where $\beta = v/c$ and $\gamma = (1 - \beta^2)^{-1/2}$. During the acceleration phase, and using the time coordinate $t$ of the accelerated frame, the spacecraft would achieve $\beta \gamma = \sinh \Theta$, with $\Theta = gt/c$. I then find that it would have traveled a rest-frame distance $d$ in accelerated time $t$ of,

$$d(t) = \int_0^t dt' c \sinh \Theta' = \frac{c^2}{g} (\cosh \Theta - 1),$$

(21)

or, equivalently,

$$\hat{t} = \cosh^{-1}(\hat{d} + 1) \longrightarrow \ln(2\hat{d}); \quad \hat{t} \equiv \frac{t}{c/g}; \quad \hat{d} \equiv \frac{d}{c^2/g},$$

(22)

where the second form applies to the limit $\hat{d} \gg 1$. Note that, because $c/g = 0.97$ yr, $\hat{t}$ can be thought of as time in years and $\hat{d}$ can be thought of as distance in light-years. Thus, to accelerate half-way to M31 and then decelerate for the remaining half of the trip, would require a total time of $2\Delta t \approx 2(c/g) \ln(\hat{d}_{M31}) \sim 29$ yr, i.e., well within a (current) human lifetime. The main, though not only, difficulty with this approach is the prodigious fuel requirements. Assuming a perfect engine, i.e., one that converted mass directly to photons (or highly relativistic particles), which were then ejected in the direction opposite to acceleration, the mass of the spacecraft would evolve as $dM/dt = -(g/c)M$, so that after the first half of the voyage

$$M_{\text{init}} = M_{1/2} \exp(\Delta \hat{t}) \longrightarrow M_{1/2} \hat{d}.$$  

(23)

Then, similarly, for the deceleration, $M_{1/2} = M_{\text{final}} \hat{d}$. Hence, $M_{\text{final}} = (\hat{d})^{-2} M_{\text{init}}$, i.e., a factor $7 \times 10^{12}$ lighter. Other problems (besides inventing the engine) include keeping teratons of
fuel (likely antimatter) stable during the 30-year voyage, and dealing with the light from M31, which would be Doppler-boosted to the MeV range. While we cannot rule out that such challenges will be met by our descendants, neither can we base our assessment of future exploration prospects on their success.

However, if the first step could be achieved, i.e., inventing the engine, then with just 0.1 year acceleration and deceleration phases, the $0.1c$ velocities that are accessible to BH slingshots, would be achieved. Using a “perfect engine”, the fuel requirement would be only about 20% of total mass. The main remaining problem would be keeping the anti-matter stable for 25 Myr.

Moreover, if this could be achieved, it would be a relatively small step to increase the acceleration and deceleration phases to $\Delta t = 1\,\text{yr}$. This would yield a coasting speed of $\beta = 1/\sqrt{2}$, which would reduce the travel time (seen from Earth) to $\sqrt{2}d_{\text{M31}}/c = 3.7\,\text{Myr}$, and the fuel storage time to 2.6 Myr. The initial-to-final mass ratio would be a very reasonable $M_{\text{init}}/M_{\text{final}} = e^2 = 7.4$.

The point is that while BH slingshots may not ultimately be the method of choice for intergalactic travel, they show that such travel is feasible. The feasibility of such travel has both near-term and long-term implications.

9. Fermi’s Paradox Revisited

Fermi’s Paradox (FP) is said to have originally been formulated in just three words: “where are they?” Slightly unpacking this: if there are technological civilizations in our Galaxy, why have they not contacted us?

If the question is formulated in this way, there are many potential answers, such as (1) no interest in contacting us, (2) conscious decision (à la Star Trek’s “prime directive”) not to interfere with other civilizations, (3) no interest in Galactic exploration, (4) inability to travel large distances (perhaps exacerbated by low density of planets that can be colonized as bases). And of course, there is the very dark explanation, that all scientific civilizations auto-destruct prior to colonizing other planets.

However, the real question, even within the context of Galactic civilizations, is not why

\footnote{Here, I distinguish between “technological civilizations”, defined as those that can send probes and/or beings to other solar systems, and “scientific civilization”, defined as those that can generate and detect electromagnetic signals. Our civilization is still at the “scientific stage”, but we can plausibly expect to reach the “technological stage” within a few centuries.}
they failed to contact us, but why they did not colonize Earth 1 Gyr ago. If such civilizations formed easily, then there were essentially as many opportunities to do so around stars that formed a Gyr before the Sun as from those having similar ages to the Sun because the rate of star formation, with similar metal abundance, was about the same 5.5 Gyr ago as 4.5 Gyr ago. Then, reasons (1) and (2) become irrelevant. That is, they would have arrived at Earth, found an excellent colonization spot that was inhabited only by single-cell organisms, and transformed the planet according to their own needs. When FP is reformulated in this way, there are really only four answers: technological civilizations are very rare (zero or a few per galaxy); planetary colonization is precluded by some physical factors (such as low density of colonizable planets or physical laws that effectively prohibit inter-planetary travel); universal lack of interest in colonization; or all scientific civilizations auto-destruct prior to, or in the course of becoming, technological.

The last two reasons require universal outcomes from completely independent social phenomena. For this reason they are intrinsically implausible. Moreover, I will argue specifically against “universal lack of interest” in Section 10. This leaves only two reasons: very few technological civilizations per galaxy or extreme difficulty of colonization. Note that the first of these two is strongly coupled to the rejection of arguments that require universal outcomes of social development. That is, if there were only two or three technological civilizations per galaxy, then it is easy to imagine that they all auto-destructed or decided not to colonize. This becomes much less plausible when there are dozens, keeping in mind that it only takes one technological civilization to colonize an entire galaxy.

The problems posed by FP become much more severe, once it is recognized that inter-galactic colonization at $0.1 \, c$ is feasible. Of course, in this paper, I have only shown that this is feasible from the standpoint of energy requirements. To actually colonize would require reconstruction of beings (humans, trans-humans, or androids) from digital data. However, given the progress in this direction in the last 50 years, it is hard to believe that it will not be achieved in the next kyr, or at least the next Myr, which is still very short compared to the several Gyr over which stars are forming. There are about 500 MW-like galaxies within 30 Mpc, i.e., within 1 Gyr travel time at $0.1 \, c$. Hence, if there were even one technological civilization per galaxy (on average) then there would be 500 such civilizations in this zone, and perhaps 150 that would have had the time needed to colonize Earth a Gyr or more

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4There are other suggested answers to FP that also require universal outcomes from independent social phenomena, such as the “dark forest” hypothesis [Liu 2008], in which all technological civilizations try to hide themselves to avoid alien attack. These are likewise plausible only if the number of such civilizations is small. In addition, regarding this particular hypothesis, if the MW is thoroughly colonized (rather than investigated by electromagnetic signals), then there is nowhere to hide.
before the present.

From this we can conclude that the number of technological civilizations per galaxy is small compared to one, or else reconstruction of beings from digital data is not physically possible.

While this discussion has been couched in developments taking place over Myr and Gyr, it actually has immediate practical implications: searching for scientific civilizations in our immediate neighborhood (e.g., 1 kpc) is very unlikely to succeed. The chance of finding one is less than \((1 \text{kpc}/R_0)^2/100 \sim \mathcal{O}(10^{-4})\). Rather, interplanetary exploration should focus on sending probes to other planets to search for living organisms, to either be analyzed locally or brought back in sample-return missions. The probability of success is orders of magnitude higher, and the scientific, economic, and cultural implications of such discoveries would be staggering. Serious effort in this direction would require investments of many trillions, and many generations would pass before real results were obtained. But these timescales are minuscule compared to the history of humanity, and even smaller compared to its future. When results eventually start to pour in, today’s childish fantasies about “Contact” with alien intelligences will be seen as an amusing footnote to the birth pangs of real exploration.

10. The Intergalactic Imperative

It may become feasible to launch probes toward M31 within a few hundred years, but there will be no compelling reason to do so at that time. For one thing, the first leg of the voyage (i.e., Earth to SgrA*) will take a few Myr, so that waiting even an additional century would likely yield technological advances that could shorten this part of the voyage by many (or hundreds) of millenia. Moreover, while such exploration could be motivated purely by intellectual curiosity, most exploration in the past has been driven by multiple considerations, not all so uplifting.

A realistic assessment of the urgency of M31 exploration and colonization will require a detailed inventory of life forms in our own Galaxy. Making use of a system of WD-binary “slingshot hubs”, it will be possible to explore the MW at 0.002\(c\) and so to survey the biological content of the entire MW in \(\lesssim 50\) Myr. Depending on the richness of that content, substantial progress might be made a factor of 10 sooner (based on the 1% of the Galaxy that is 10 times closer). This survey will permit direct evaluation of most terms in the Drake equation. For example, we might find that, apart from Earth, the MW is entirely sterile. Or, we might find that unicellular life is ubiquitous, but there are only a handful of planets that have reached the stage of an energy-rich environment (probably based on free oxygen,
but maybe something else), and none have multi-cellular animals. Such survey outcomes would support the hypothesis that technological civilizations are truly rare, and plausibly non-existent within 30 Mpc (or whatever distance could plausibly be traveled in a Gyr based on technologies developed over the next few Myr). Under these conditions, there would be no compelling necessity to colonize of M31, and efforts might well be focused on the prodigious opportunities for colonization in the MW.

However, it is also possible that the survey will find thousands or millions of planets with multi-cellular organisms, with progressively smaller subsets reaching progressively higher levels of development. This would permit not only direct measurement of many known terms in the Drake equation, but also the identification of new ones. For example, perhaps there will be dozens of planets with complex agricultural civilizations that have existed for many Myr, but with no mathematical physics, so no concept of Maxwell’s equations, let alone quantum mechanics. Perhaps, instead (or in addition), there will be dozens of planets with the buried ruins of complex civilizations that had reached (or approached) the technological stage.

Contrary to current infantile thinking, either of these possibilities would be extremely alarming. They would mean that the raw material for technological civilizations is extremely widespread and only one or two steps from those beings gaining the ability to leave their planets and start colonizing. In particular, the latter possibility (dozens of auto-destructed civilizations) would present a lurid picture of what such civilizations would be capable of if they ever did start colonizing.

One might hope that any alien technological civilizations that were encountered would be populated by angelic beings (or trans-beings), interested only in helping anyone they met to achieve a higher level of consciousness. Indeed, this might turn out to be true. However, without any specific evidence in favor of this pleasant thought, one should prepare for the opposite possibility, that their inter-galactic colonization was at least driven by defensive military considerations (see below), if not a direct outcome of their victory in their own internal wars and/or inter-alien wars.

The only way to block such alien colonization efforts in the MW would be to occupy all planets where the aliens could potentially gain a foothold. And then to begin occupying neighboring galaxies, both to forestall, and to warn of, their approach. The fact that the characteristic timescale of such an approach is Gyr (i.e., the timescale of galaxy evolution), would not lessen the urgency because the timescale of colonizing our own “sphere” of galaxies within 30 Mpc would be essentially the same. Note that the very act of setting up such a defensive colonization system would likely be seen as potentially hostile by alien civilizations, and the anticipation of just such possibilities would have been one (of possibly several) of
their own motivations for expanding.

11. BH Slingshot: A Poor Man’s Wormhole

About 30 years ago, I attended a public lecture about Einstein by a famous mathematical physicist. To illustrate the Principle of Equivalence, the speaker invited the audience to consider a trip in an “elevator cabin” that was falling freely through an evacuated tunnel going straight through Earth (presumably on the polar axis, though he did not specify). If the cabin had no windows, the speaker claimed that people in the elevator would have no way to tell that they were accelerating and decelerating through Earth from one side to the other, and that they were not floating freely in space.

After the lecture, I approached the speaker and politely told him that there was such a method to distinguish the two situations: simply hold out one’s arm and release a ball. For the person falling through Earth, the ball would fall toward his feet and then rise again to his arm, while in free space, the ball would just stay by his arm.

The speaker insisted that he was correct, and, perhaps mistaking me for a member of the general public, pedantically lectured me for about a minute that there were no known exceptions to the Principle of Equivalence.

In fact, the elevator example does not contradict the Principle of Equivalence because this principle applies only to local observers, where “local” means local in 4-space, i.e., in both space and time. “Local in space” means small compared to the gradient of the gravitational field, and “local in time” means short compared to a dynamical time.

In particular, tidal effects will always generate order-unity phenomena if allowed to persist unopposed for a dynamical time.

At first sight, the BH slingshot appears to be a “cost free” method for accelerating to \(0.1\ c\) in of order \(0.1\) seconds. The spacecraft is in free fall and so does not experience any inertial forces. Hence, it might appear that there could be a human passenger who likewise is brought to \(0.1\ c\) in \(0.1\) seconds (without “feeling” any accelerating forces), compared to the 36 days that this would require at \(\sim 1\ g\) acceleration. In starting out with this naive reasoning, one can almost hear Milton Friedman cautioning that “there is no such thing as a free lunch”, but within the Equivalence-Principle elevator framework of the above-mentioned

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\(^5\)If Earth were of uniform density, this motion would be exactly synchronized with the position of the elevator relative to Earth’s center.
speaker, one is tempted to ignore tides. In reality, however, the BH slingshot operates (by
construction) on a free-fall timescale, so tides have an order unity effect. These order-unity
tidal effects are Friedman’s “cost” of the “free” acceleration to semi-relativistic speeds.

A (say, spherical) collection of particles with no forces between them will, in slingshot
in-fall, change their collective shape into an elongated ellipsoid, and then splatter during exit.
This is true in exactly the same way for a BH slingshot as a Jupiter slingshot. The difference
is only in the level of inter-particle forces that are required to counter the tidal forces. For a
Jupiter slingshot, the roughly spherical human brain would at all times maintain its shape
in the face of the tidal forces, whereas for a BH slingshot it would not (even if the skull could
be kept in place by mechanical support).

In this sense, the BH slingshot can be considered intermediate between a Jupiter slingshot
and wormhole transport in efforts to evade the normal requirements of transport by
“\( F = ma \)” via more complex gravitational fields. There is always a “price” (insurmountable
for material objects in the case of wormholes), with the benefit generally proportional to the
cost.

However, the BH slingshot method could be made more human friendly by considering
larger orbiting BHs. I have assumed that the BHs orbiting SgrA* have \( M = 5 M_\odot \), but recent
work has shown that the BH mass function may well be centered at twice this value and
cover a broad range of masses. And in the dense environment of the Galactic center, there
could be substantially more massive BHs, e.g., \( M = 30 M_\odot \), such as have been detected
in LIGO observations. At fixed infall velocity (so fixed \( M/q_{bh} \)), the tidal forces scale as
\( M/q_{bh}^3 \propto M^{-2} \), so they would be \((30/5)^2 = 36\) times weaker than I have calculated. This
could be used to increase the ejection speed by a factor \( 6^{1/3} = 1.8 \) (see Equation (3)), or
it could be used to have 36 times less stressful tides. It is unlikely that this would reach a
level that was safe for humans, and in any case, there does not (at present) seem to be any
application for such human slingshots at the Galactic center. Nevertheless, a less stressful
slingshot could be important for transporting more complex equipment.

The idea that tides produce order-unity effects if allowed to develop over a dynamical
time (and so “violate” a misconstrued version of the Principle of Equivalence) seems obvious.
However, many “obvious” things remain unrecognized until they have been pointed out (or,
as in the case of the speaker, even after they have been pointed out). More to the point, the
significance of “obvious” ideas is often missed until they are explicitly formulated.

Stating this “obvious” point in another way, gravitational phenomena that arise only
on a dynamical timescale are tidal in nature and are therefore not subject to the Principle
of Equivalence. An interesting example is the emission of Hawking (1975) quanta. The
BH temperature (in units $\hbar = c = 1$) is $T = 1/8\pi M$, so (including those quanta that are eventually reflected back into the BH), the number of quanta emitted per dynamical time $t_{\text{dyn}} \approx \sqrt{R_{\text{Sch}}^3/M} = \sqrt{8}M$ is

$$N = \frac{6\zeta(3)}{\pi} T^3 4\pi R_{\text{Sch}}^2 \sqrt{8}M = \frac{3\sqrt{2}\zeta(3)}{8\pi^3} \approx 0.02.$$  (24)

12. Conclusions

Intergalactic exploration by robotic spacecraft at speeds of $\sim 0.1c$ is feasible based on technologies that either exist today or can be developed based on our present understanding of physics and materials. The key intellectual innovations that allow this are first, using the small BHs that orbit the supermassive BHs at the centers of galaxies as sling shots, and second, using gravitational microlensing to navigate these sling-shot encounters to high ($\sim 1\text{ km}$) precision.

Conceptually similar, but much weaker sling shots from WD binaries could enable exploration of the MW at $\sim 0.002c$, permitting complete exploration of our Galaxy in about 50 Myr.

I have argued through several steps that the practical possibility of intergalactic travel implies that either “technological civilizations” are rare ($\lesssim 0.01$ per MW-like galaxy), or it is physically impossible to reconstruct intelligent beings (human-like, trans-human-like, or robotic) from digital data. Here a “technological civilization” is defined as one that is capable of sending robotic spacecraft to other solar systems.

To briefly recapitulate, if there were an average of even 1 such civilization per galaxy, then there would be 150 capable of reaching Earth at a time when Earth had only unicellular life. Hence, there would be no compelling reason not to colonize it. If astro-biological investigation of their own galaxy showed that technological civilizations were feasible (even if not actually present there), these aliens would face an “intergalactic imperative” to colonize all planets in whatever galaxies they could reach (including ours) as a defensive measure. Always provided that it is actually possible to reconstruct beings from digital data, this would be an exponential process, limited only by spacecraft travel time, using essentially unlimited resources of other planets, so there would be no physical barriers to stop this process. All counter-arguments rest on theories of universal social development by completely independent societies. Our own experience on Earth, even with physically very similar people in different places, shows that such convergent social evolution is beyond unlikely.

The main immediate conclusion is that looking for electromagnetic signals from alien
civilizations in the solar neighborhood is not likely to be productive. While such “scientific civilizations” (i.e., like our own) are a few steps below “technological civilizations” and therefore somewhat more common, this effect is actually small. The time between the two phases is likely measured in centuries, compared to the Gyr timescales of galactic evolution that govern the “intergalactic imperative”. Only if the overwhelming majority of all such civilizations auto-destructed would there be any serious chance of finding one in our own neighborhood.

Hence, the main conclusion that one could draw from the detection of even one such “scientific civilization” is that we are not long for this world.

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Fig. 1.— Ejection speed of test particle, $v_2$, scaled to speed of the spacecraft at peribothron of the small BH ($c/\sqrt{n}$) as a function of the angle $\phi$ of the spacecraft velocity relative to the small-BH orbital direction. Curves are shown for five values $N/n$, where $n$ is the number of small-BH gravitational radii of the test particle at peribothron and $N$ is the number of large-BH gravitational radii of the orbit of the small BH. As shown in Section 3, $n$ is limited by tidal effects and the tensile strength of the spacecraft, but could plausibly be $n \sim 100$. The curves show that ejection velocities $v_2 \sim c/\sqrt{n}$ are generally achievable, provided that $N \lesssim n$. 

\[ \frac{n^{1/2}}{v_2/c} \]
Table 1. M31 Voyage/Colonization

| Phase                     | Dist. (kpc) | Speed (c) | Time (Myr) |
|---------------------------|-------------|-----------|------------|
| Earth–(WD$^2$)            | 0.03        | 0.0007    | 0.15       |
| (WD$^2$)–SgrA*            | 8.1         | 0.002     | 13         |
| SgrA*– M31                | 780         | 0.1       | 25         |
| Explore/Colonize          | 20          | 0.002     | 33         |
| M31–Earth$^a$             | 780         | 0.1       | 25         |

Note. — a: optional