Letter

# Sensitive searches for wormholes

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A sensitive test for whether a black hole is a wormhole, using astronomical observations, would be to look for perturbations in the orbit of a pulsar around the black hole, caused by a perturbing object on the other side of the wormhole. By observing a pulsar in an orbit like that of S2 around the supermassive black hole at Sgr A* at the center of our Galaxy, the attainable mass limit on the perturber would be approximately $10^4$ times better than derived from current observations of S2. For a nominal stellar-mass black hole–pulsar binary, observing for 1 year could set a mass limit on a perturber more than 6 orders of magnitude better than for a pulsar orbiting Sgr A*. Observations of a star in a stellar-mass binary containing a black hole could set limits similar to the case of a pulsar orbiting Sgr A*.

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## I. INTRODUCTION

Might some black holes be wormholes? Black holes resulting from stellar evolution are not expected to be wormholes [1]. However, it has been argued that supermassive black holes may have a primordial formation history [2]. Furthermore, even some stellar mass black holes in binary systems may be primordial [3]. It has been argued that primordial wormhole formation is possible and may be linked to primordial black hole formation [4]. Recently, it has even been claimed that a ninth planet (aside from Pluto) in the solar system might be primordial in nature [5].

Can observations be used to test if specific black holes are wormholes? We explore a proposal, first discussed by Ref. [6], to look for the effect on the orbit of an object on our side of the wormhole due to a perturbing object orbiting on the other side of the wormhole (for other methods, see, e.g., Refs. [7–17]). Can we reasonably expect perturbers to orbit on the other side of a wormhole? It is well known that most stars are members of binaries, triple systems, etc. Thus, it is more likely that a stellar-mass black hole is a member of a multicomponent system; an orbiting perturber on the other side of the wormhole is a reasonable scenario.

We will consider potential observations of black hole–pulsar binary systems, which can provide sensitive searches for a wormhole. Importantly, the existence of black hole–neutron star (BH-NS) systems has been confirmed by LIGO [18,19]. Furthermore, a population of black hole–neutron star binaries is suggested to be present near the Galactic Center [20].

The fascinating study of wormholes goes back to Einstein and Rosen (ER) in 1935 [21]. This work was then explored in the 1950s and 1960s by John Wheeler [22] and collaborators, who have emphasized the importance of wormholes (and topology change) in quantum gravity [23]. In the 1980s Baum [24], Hawking [25], and Coleman [26] focused on the role of topology change in Euclidean quantum gravity (see Ref. [27] for a review), and they speculated that this process is crucial for the possible fix of fundamental constants in nature and, in particular, the cosmological constant (see also Ref. [28]). In a different research direction, but around the same time, Kip Thorne and collaborators realized that it was possible to construct "traversable" wormhole solutions [29,30]. (For an illuminating review of this work, consult Ref. [31].) More recently, there has been a lot of activity on the subject of wormholes and quantum entanglement since the ER = EPR proposal [32] (see also Refs. [33,34]).

Where could such wormhole candidates come from? One obvious source is the quantum gravity phase of the very early Universe. Even though such configurations would be exponentially suppressed, inflation might make them macroscopic and thus potentially observable. Their number has to be very small, so that observed structure formation is not affected. Thus, observing such remnant wormholes would be very challenging but, in principle feasible, as explained in this paper.

 

## II. OBSERVABLE EFFECTS OF A WORMHOLE

It is a fascinating possibility that such a wormhole solution can be actually observed. One approach has been recently addressed in Ref. [6], and here we just summarize the main result. Consider a simple wormhole model which can be studied analytically. A standard Schwarzschild space-time metric with the gravitational radius $r_g = 2GM/c^2$ is given as

$$ds^2 = -\left(1 - \frac{r_g}{r}\right)dt^2 + \frac{dr^2}{1 - \frac{r_g}{r}} + r^2 d\Omega. \tag{1}$$

We cut this space-time at the radius $R$, which is slightly bigger than the gravitational radius, i.e., $R \geq r_g$. We take another identical space-time and paste them together. Our global construct is thus two copies of the Schwarzschild space-time connected through a mouth of radius $R$. This setup represents a short throat wormhole, which is traversable since $R \geq r_g$. Some exotic matter with negative energy density is needed to keep the wormhole open; however, in the short throat approximation that we use, we assume that the effects of this exotic matter are subdominant. This assumption can further be supported by noticing that an arbitrarily small amount of negative energy might be sufficient to stabilize the wormhole, as argued in Ref. [35].

We consider a situation in which the object we observe is located in our space, while a perturber, i.e., an object orbiting on the other side of the wormhole, has an elliptical orbit with the periapsis radius $r'_p$ and apoapsis radius $r'_a$. All parameters referring to the perturber on the other side of the wormhole will be primed; all parameters referring to the perturbed object on our side (and thus directly observable) will be unprimed. The magnitude of the acceleration variation of the object in our space is

$$\Delta a = GM'R\left(\frac{1}{r'_p} - \frac{1}{r'_a}\right)\frac{1}{r^2}, \tag{2}$$

where $r$ is the radial coordinate in our space and $M'$ is the mass of the perturber. If the orbit of an object on the other side of the wormhole's is elongated so that $r'_a \gg r'_p$, then we can approximate the magnitude as

$$\Delta a \approx GM' \frac{R}{r'_p}\frac{1}{r^2}. \tag{3}$$

Note that what we calculate in Eq. (3) is the magnitude of acceleration variation of an object in our space due to an elliptical orbit of a perturber on the other side perturbing the metric. These variations come on top of the constant acceleration that comes from the central object. With good enough precision, we should be able to detect or exclude this variable anomalous acceleration. Other variations could be produced by some other dim sources on our side. Then, more careful modeling would be required to distinguish between different options.

It is important to note that our wormhole has Schwarzschild geometry outside of the mouth, while the horizon is not present at all, since we cut the Schwarzschild geometry at $R > r_g$. Thus, such wormholes can be harbored both by black hole candidates (either stellar mass or supermassive) and/or other compact objects less massive than black holes. In particular, a neutron star candidate might as well be a wormhole, as long as we do not see its surface.

## III. SEARCHING FOR WORMHOLES

Dai and Stojkovic [6] considered observations of the star S2 in orbit around the supermassive black hole (BH) at the center of our Galaxy, at Sgr A*, to produce tentative limits on a perturber, if the BH is a wormhole.

The most direct way to observe the effect of the anomalous acceleration shown in Eq. (3) is to look for deviations of the object's orbit from the expected, unperturbed Keplerian or general relativistic (GR) result. The observable most directly connected to the physical argument is an additional, periodic variation in the orbital velocity, i.e., the Doppler velocity of the object on our side. Our goal in the subsequent calculations is not to precisely determine the limits on the perturber that one can obtain but to produce roughly approximate limits indicative of how one can set the best limits by observing a pulsar in the cases we consider. And, therefore, we will use simplifying assumptions that ignore geometric factors of order unity and other similar choices.

To estimate the change in the orbital velocity caused by $\Delta a$ given in Eq. (3), we assume, for simplicity, that the additional acceleration occurs once every orbital period $T'$ of the perturber (i.e., when it is near its periapsis). We will consider systems where the duration of the additional acceleration $\Delta a$ (i.e., the time the perturber is near its periapsis) is $t'_p \ll T$, where $T$ is the orbital period of the perturbed star on our side of the wormhole, so we treat the effect of the perturber on the object we observe as impulsive. We also have $t'_p \ll T'$, of course. We estimate the magnitude of the change in the observed object's velocity caused by *one* such impulse, as

$$\delta v \sim \Delta a\, t'_p \sim GM' \frac{r_g}{r'_p}\frac{1}{r^2}\, t'_p. \tag{4}$$

To estimate $t'_p$, we note $T' = t'_p + t'_a \sim t'_a$, where $t'_a$ is the time the perturber spends away from periapsis (i.e., mostly at apoapsis for $r'_a \gg r'_p$). So, where $v'_p$ and $v'_a$ are the periapsis and apoapsis speeds of the perturber, respectively, we have

$$t'_p \sim t'_p \frac{T'}{t'_a} \sim \frac{r'_p}{v'_p} \frac{v'_a}{r'_a} T' \sim \left(\frac{r'_p}{r'_a}\right)^2 T' \sim f'^2 T', \quad (5)$$

where $f' = r'_p / r'_a$, and we used $v'_a r'_a = v'_p r'_p$ by conservation of angular momentum. The eccentricity of the orbit of the perturber is $e = (1 - f')/(1 + f')$. Thus, Eq. (4) for $\delta v$ becomes

$$\delta v \sim GM' \frac{r_g}{r'_p} \frac{1}{r^2} f'^2 T. \quad (6)$$

While resonant or chaotic behavior could produce obvious secular changes in the perturbed object's orbital parameters, the goal of this paper is to set limits on the mass of the perturber absent any such extreme effects. Furthermore, we argue that secular effects are not likely for two reasons. First, note that the additional acceleration is caused by a potential which is proportional to $1/r$, and is oscillatory. Secular effects would be caused by a monotonically increasing/decreasing $1/r$ potential. Indeed, in the limit $T' \ll T$ (which is the limit we will consider), the long-term effect of the perturber is as if the mass of the black hole were slightly larger, producing a Keplerian (or GR) result for the object we observe. The second argument is based on studies of secular effects in the solar system. For example, secular changes in the argument of perihelion of a planet can be explained mainly by the nonspherical, long-time-average mass distribution of each other planet, equivalent to the quadrupole mass distribution of a ring, centered on the Sun, of mass and radius equal to the mass and orbital radius of the perturbing planet [36]. The long-term average is on a timescale much greater than the orbital period of the perturber but much less than the timescale of any secular orbital change. In our case, the long-term average effect is that of a constant monopole potential, producing a Keplerian (or GR) result.

A potentially observable, less-than-extreme effect, would be an oscillating Doppler velocity due to the perturbations, with period $T'$, on top of the unperturbed orbital Doppler velocity behavior of period $T$. Here, we consider only perturbations with period $T' \ll T$, which would be more readily separated from the unperturbed time-varying Doppler velocity of period $T$, or from other longer timescale effects that might be present due to, for example, perturbations caused by other objects on our side of the wormhole.

After modeling and removing the unperturbed orbital behavior of the Doppler velocity of our observed object, if an additional cyclic variation of some period $T' \ll T$ is not readily apparent, the best strategy to search for such a result is to cut the sequence of velocity residuals into segments of some duration $T'$. Then, stack and average the sequences. In this way, one could detect a cyclic variation in Doppler velocity of period $T'$ as the noise in the resulting measurements is reduced by $\sqrt{\tau/T'}$, where $\tau$ is the duration of the observing program. Searches for a range of $T'$ would be necessary. A particularly elegant and systematic tool for accomplishing this search for a cyclic result is the Lomb-Scargle periodogram, which is especially useful for datasets which are not sampled periodically or are missing samples [37,38].

If this search procedure does not make apparent any cyclic perturbation, then individual perturbations in Doppler velocity must satisfy

$$\delta v \lesssim \sigma_v \left(\frac{T'}{\tau}\right)^{1/2} \quad (7)$$

for each $T'$ in the search, where $\sigma_v$ is the uncertainty in an individual Doppler velocity measurement. To the precision for which we are calculating results, a geometric factor of order unity has been ignored. Then, from Eq. (6), an upper mass limit on the perturber is

$$M' \lesssim \frac{1}{G} \frac{r'_p}{r_g} r_{\mathrm{avg}}^2 \frac{1}{f'^2 T'} \sigma_v \left(\frac{T'}{\tau}\right)^{1/2}, \quad (8)$$

where $r_{\mathrm{avg}}$ is the average distance of the observed object, on our side, from the wormhole (i.e., the semimajor axis of the object's orbit). Since $T' \propto r'^{3/2}_p$, this limit is $\propto r'^{1/4}_p$.

To determine attainable numerical mass limits on $M'$, we first consider the case of S2 orbiting the supermassive BH at Sgr A*. For observations of S2, we have $\sigma_v \sim 10$ km/s [39]. We note that modeling of the nonperturbed motion of S2 (to be removed first before searching for the effects we are studying) would need to take account of the effects of general relativity and a diffuse distribution of dark matter near Sgr A*, as explained in detail by Ref. [40]. This unperturbed motion of S2 includes secular behaviors such as periapsis precession (which has been observed by Ref. [41]). For all the cases we consider in this paper, we take $f' = 0.1$. We choose $f' = 0.1$ as a rough representation of an elliptical orbit, which makes the use of Eq. (3) reasonable. For $M_{\mathrm{BH}} = 4 \times 10^6\ M_\odot$, we obtain a mass limit for a perturber as a function of $r'_p / r_g$ given by the uppermost dotted line in Fig. 1.

A better limit could be set from observations of a star in orbit around a stellar-mass BH, instead of the supermassive BH at Sgr A*. The cleanest systems would be those with no mass transfer, which would avoid dynamical changes not caused by a perturber on the other side of the wormhole. Recently, there were suggestions that such systems had been discovered [42,43]. However, subsequent work suggests these systems do not contain BHs [44–47]. Nevertheless, since such a system could be found, we consider here possible limits on the perturber mass that could be obtained for a generic system inspired by these observations, with a $10\ M_\odot$ BH, stellar orbit of radius approximately $10^6 r_g$, and individual Doppler velocity

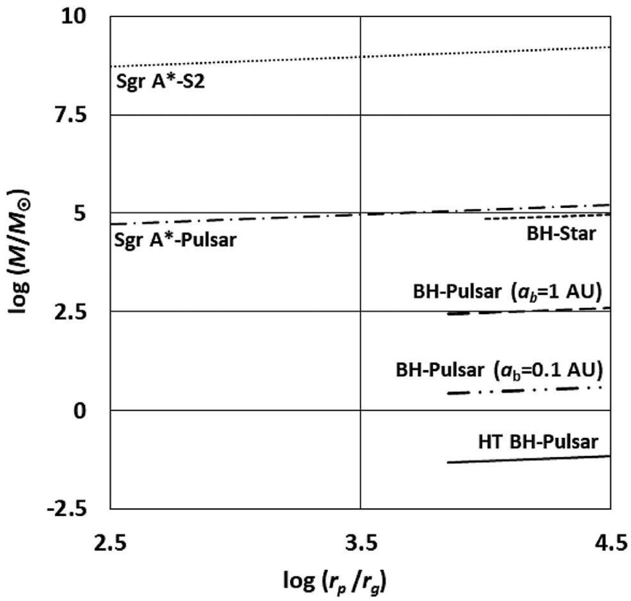


FIG. 1. The mass limit on the perturber as a function of its periapsis distance from the wormhole (expressed in units of the gravitational radius of the BH/wormhole). The Sgr A*-S2 line is for observations of S2 orbiting the supermassive BH at Sgr A*. The BH-star line is for observations of a generic binary system comprising a star and stellar-mass BH. The other lines are for binary systems consisting of a pulsar and stellar mass BH. The HT BH-Pulsar case is for a BH-pulsar binary of size similar to the Hulse-Taylor (HT) binary pulsar system.

measurements for the star with $\sigma_v \sim 6$ km/s (about $\sqrt{100} = 10$ times larger than the uncertainty in the amplitude of the fitted model for the Keplerian orbital Doppler velocity in such systems, assuming approximately 100 observations were used). The perturber mass limit for this case could be approximately 4 orders of magnitude lower than obtained from observations of S2 and is shown by the short-dashed line in Fig. 1, for $\tau = 1$ year.

However, observations of a pulsar orbiting a BH have the potential to set even better limits, given the greater observational precision attainable. BH-pulsar binaries have been argued to provide remarkable tests of quantum gravity [48–54] on top of their proven record in testing Einstein's general relativity in the case of the Hulse-Taylor BH-pulsar binary PSR B1913 + 16 [55].

The uncertainty in a measured Doppler velocity for a pulsar at a particular epoch depends on the precision with which the frequency of the observed pulses can be determined for that epoch. The precision on measured parameters for a pulsar is determined by the precision on pulse "times of arrival" (TOA) measurements, which is typically $\sigma_{TOA} \sim 1$ $\mu$s [56]. A pulse TOA measurement is obtained from $\tau_{TOA} \sim 1$ min of data at each observing epoch (during which a folding and pulse-shape averaging process is applied); see the discussion in Ref. [56], for example. The result is one TOA for that epoch. The pulse frequency for that epoch is $\nu = n/\tau_{TOA}$, where $n$ is the number of pulses arriving during the time interval $\tau_{TOA}$ (known accurately from the folding process). The precision on $\tau_{TOA}$ is $\sim\sigma_{TOA}$. Thus, the uncertainty in the pulse frequency for that epoch is

$$\sigma_\nu \sim \frac{n}{\tau_{TOA}^2} \sigma_{TOA}. \tag{9}$$

Finally, since any variation in the Doppler velocity is determined from the observed pulse frequency, the uncertainty in the Doppler velocity is

$$\sigma_v \sim \frac{\sigma_\nu}{\nu} c \sim \frac{\sigma_{TOA}}{\tau_{TOA}} c \tag{10}$$

or approximately 1 m/s for pulsar observations. This is very much better than attained for observations of an ordinary star ($\sigma_v \sim 10$ km/s), owing to the precision with which pulse TOA measurements can be made; this increased precision for pulsar observations is at the heart of our argument. We have chosen a particularly good TOA uncertainty (1 $\mu$s), which would be obtained for a good millisecond pulsar. But there is some theoretical work that suggests BH-NS binaries may mostly contain normal pulsars, in which case the results would not be as good [57].

For a pulsar in an orbit around Sgr A* which is similar to that of S2, using $\sigma_v \sim 1$ m/s, we obtain a mass limit for the perturber that is approximately 4 orders of magnitude lower than for observations of S2. The result is the dot-dashed line in Fig. 1. We used $\tau = 15$ years because observations should stretch over at least the orbital period to model and remove the unperturbed motion before searching for Doppler variations caused by a perturber. Note the limits for this case would be similar to those one might obtain for a generic star-BH binary of stellar masses.

Still better results could be obtained for pulsars in close orbits around stellar-mass black holes. Consider the "nominal" case of a pulsar in orbit around a 10 $M_\odot$ BH where $r_{\rm avg} \approx 2 \times 10^9$ m, the semimajor axis for the Hulse-Taylor pulsar. For observations over $\tau = 1$ year, and $\sigma_v \sim 1$ m/s, we obtain a limit on the perturber mass more than approximately 6 orders of magnitude better than for a pulsar orbiting Sgr A*, at comparable $r'_p$. This result is shown by the solid line in Fig. 1. This line is drawn only for $\log(r_p) > 3.9$ which ensures $fT > \tau_{TOA}$.

We now consider a population of BH-pulsar binaries that may be present in the Galactic Center [20]. The semimajor axes of these binaries would range from approximately 0.1 A.U. to approximately 1 A.U., with eccentricities approximately 0.8. Using $M_{\rm BH} = 10$ $M_\odot$ and $\tau = 1$ year with $\sigma_v \sim 1$ m/s, the perturber mass limits attainable for these systems are below the limit for a pulsar orbiting Sgr A*, but not as low as the nominal Hulse-Taylor–sized pulsar-BH binary. These results are also shown in Fig. 1, labeled by the sizes of the semimajor axes.

## IV. OBSERVATIONAL PROSPECTS AND OUTLOOK

The best prospects for identifying stable BH-NS systems stem from either gravitational wave detection with a follow-up search for pulsar emission or the direct detection of pulsars in a binary system followed by determination of the nature of the binary partner. LISA is designed to detect stable binary systems including BH-NS systems [58]. The SKA is designed to be able to detect all the pulsars in our Galaxy including near the Galactic Center where BH-pulsar systems may be more common [59]. In future work, we plan to use numerical simulations to further explore the perturber limits that can be obtained. We will also explore connections with the recent research on quantum gravity/string theory [60] with intrinsic nonlocality that could be probed as outlined in this paper.

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