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OBSERVABILITY OF PULSAR BEAM BENDING BY THE Sgr A* BLACK HOLE

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ABSTRACT
According to some models, there may be a significant population of radio pulsars in the Galactic center. In principle, a beam from one of these pulsars could pass close to the supermassive black hole (SMBH) at the center, be deflected, and be detected by Earth telescopes. Such a configuration would be an unprecedented probe of the properties of spacetime in the moderate- to strong-field regime of the SMBH. We present here background on the problem, and approximations for the probability of detection of such beams. We conclude that detection is marginally possible with current telescopes, but that telescopes that will be operating in the near future, with an appropriate multiyear observational program, will have a reasonable chance of detecting a beam deflected by the SMBH.

Key words: black hole physics – Galaxy: nucleus – pulsars: general

Online-only material: color figures

1. INTRODUCTION
Near-infrared observations of stars near our Galaxy’s central supermassive black hole (SMBH) have revealed a larger number of young, massive stars than can be explained by typical star formation models (Ghez et al. 2005; Eisenhauer et al. 2005). This “paradox of youth” (Ghez et al. 2005) has pointed to the development of a possible continuing top-heavy initial mass function (IMF) in the region near the central SMBH (Maness et al. 2007; Nayakshin & Sunyaev 2005). A top-heavy IMF near Sgr A* would imply the existence of a large number of neutron stars in close proximity to the central SMBH. Current estimates suggest that there could be \( \gtrsim 10^4 \) neutron stars within 1 pc of Sgr A* (Muno et al. 2005), comprising one component of a cusp of massive stellar remnants in the Galactic core (Freitag et al. 2006; Hopman & Alexander 2006). X-ray observations have been consistent with this number of neutron stars (Deegan & Nayakshin 2007) but appear to have ruled out the presence of a larger number of neutron stars (e.g., 40,000). In the innermost regions, the number of pulsars within \( \sim 0.017 \) pc of Sgr A* could be as high as \( \sim 1000 \) (Pfahl & Loeb 2004), where we take the central SMBH mass to be \( 4 \times 10^6 M_\odot \). For this paper, we will assume the optimistic population density of 1000 pulsars within 0.017 pc of Sgr A*; our results can readily be scaled to more conservative population estimates. We will also follow Pfahl & Loeb in assuming that \( n(r) \), the density of pulsars as a function of distance from the Galactic center, falls off as \( r^{-3/2} \), so that

\[
n = \frac{3}{8\pi} \times 10^6 \text{ pc}^{-3} (r/1 \text{ pc})^{-3/2}. \tag{1}
\]

In this paper, we will consider the possibility that an appropriate program to monitor pulsar beams from Sgr A* would detect a beam that is strongly deflected by the central SMBH. Such a system would be of great interest, as precision timing of the radio pulses from such a system would measure the properties of the spacetime through which they propagate. Preliminary work in the case of Schwarzschild black holes, presented in Wang et al. (2009b) and Wang et al. (2009a) (hereafter Paper I and Paper II), has revealed a rich structure and multiplicity of pulses observed in such geometries; subsequent work will look at how pulse timing can be used to measure properties such as the mass and spin of the SMBH, and measure or constrain deviations in the higher multipoles of the spacetime from the predictions of general relativity. In the present paper we will focus on determining the likelihood of observing a pulsar in such a configuration. To do this we will first calculate the probability that a single pulsar, in orbit around the central SMBH, emits a signal in such a way that it is strongly deflected by the central SMBH, and reaches the Earth. From this we then infer the probability that the signal from one of the assumed number of pulsars is strongly deflected, reaches the Earth, and is detectable by radio telescopes.

The paper continues in Section 2 with a discussion of the model for the pulsar–SMBH system, and with assumptions about pulsar characteristics and telescope sensitivities. The heart of the paper is the method of computation of probabilities in Section 3. Numerical estimates of probability, based on this approach, are given in Section 4, and considerations for an observing program are given in Section 5. In Section 6 we conclude that an observing program, even with current radio telescopes, would have some chance of detecting strongly bent pulsar emissions, while later generations of telescopes will significantly increase the likelihood of observing these fascinating systems.

2. BACKGROUND, MODEL, AND ASSUMPTIONS
As a simplification in our probability estimates we take the SMBH in Sgr A* to be a Schwarzschild hole. It is essentially certain, of course, that the SMBH is rotating, but the angular momentum \( J \) is currently thought to be less than or of order half of its maximum possible value of \( GM^2/c^3 \), where \( M \) is the mass of the SMBH (Melia et al. 2001; Genzel et al. 2003), with some authors finding that observations are consistent with zero spin (Broderick et al. 2011). Typically, the astrophysical properties of Kerr holes differ significantly from those of Schwarzschild holes only when \( J \) is very close to \( GM^2/c^3 \). Our preliminary investigations of Kerr holes, in work now underway, confirm this.

While frame dragging by the black hole may slightly increase the probability of detecting beams bent in the prograde sense, and decrease the probability of retrograde-bent beams, these effects largely cancel when considering the population as a whole. Thus the Schwarzschild approximation would appear to
be justified for our purposes, in which it is the average properties that are of importance.

We will rely heavily on results in Papers I and II for pulsar beam deflection around a Schwarzschild hole. In those papers \( \phi_{in} \) is the angle between the direction of pulsar emission and the direction radially outward from the central SMBH at the emission event; the angle \( \phi_{out} \) is the angle between that same initial radial direction and the direction in which the pulsar beam is moving when it is asymptotically far from the SMBH, as sketched in Figure 1. In the absence of the bending of the beam, the two angles \( \phi_{in} \) and \( \phi_{out} \) would be equal. The effect of curvature of the beam is encoded in the function \( F \) defined by

\[
\phi_{out} = F(\phi_{in}; r_0),
\]

where \( r_0 \) is the distance of the emission point from the SMBH.

The computational method for finding the \( F \) function is discussed in Papers I and II. A practical approximation for \( F \), useful for the considerations of this paper, is presented in the Appendix.

With the simplification to a nonrotating SMBH, we do not need to consider any angle between the orbit of the pulsar and the spin axis of the SMBH. The geometric parameters of interest are pictured in Figure 2. The inclination of the pulsar spin axis with respect to the orbital plane is denoted as \( \lambda \); the beam of pulsar emission is taken to have its center at angle \( \alpha_0 \) from the spin axis, and to have width angular width \( 2\Delta\alpha \), so that the pulsar emission is confined between conical surfaces with opening angles \( \alpha_0 - \Delta\alpha \) and \( \alpha_0 + \Delta\alpha \), as shown in Figure 2.

In Figure 2, \( r_0 \) denotes the radial distance of the pulsar from the SMBH at the moment of emission of a beam. We do not assume circular orbits in our probability calculations except in the calculations of orbital times in Section 4.

We will assume that there is no favored alignment of the pulsar spin axis with the pulsar orbital plane, and will take \( \lambda \) to be uniformly distributed over the sky. Within a fraction of a pc from the central SMBH, we expect there to be no significant alignment of the neutron star population with the disk of the Galaxy, so we will take the orientation of the orbital plane also to be randomly distributed over the sphere.

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\[
\frac{I}{I_0} = \frac{\sin \phi_{in}}{\sin (F) (dF/d\phi_{in})}. \tag{3}
\]

As a step in understanding how much reduction can be allowed if a pulsar beam is to be observed, we start with the radio luminosity at 1.4 GHz (\( L \) band). We will choose our radio luminosities from two separate distributions. The first distribution is from all pulsars for which this quantity has been calculated in the ATNF Pulsar Catalog (2010). In this case, the distribution of pulsar \( L \)-band flux densities \( S \), observed at the Earth, would be that shown in Figure 4. Since there are likely to be selection effects present in the distribution of known pulsar luminosities, we will also calculate our probabilities from values chosen from a second distribution described in Faucher-Giguère & Kaspi (2006, Stovall et al. [2008]).
hereafter FGK). This second distribution is a lognormal distribution with \( \mu = -1.1 \) and \( \sigma_{\log L} = 0.9 \), which when moved to the Galactic center gives a lognormal distribution with \( \mu = -2.9 \) while \( \sigma_{\log L} \) is unchanged. We present observability results separately for each assumed distribution in Section 4.

While we have used \( L \)-band luminosities above, a search for pulsars near the Galactic center will require observations at \( C \) band, \( X \) band, or \( Ku \) band (4–8 GHz, 8–12 GHz, and 12–18 GHz, respectively) to overcome the effects of scattering from plasma in the Galactic cusp. Cordes & Lazio (1997) argue that observations around 10 GHz are optimal, whereas Kramer et al. (2000) contend that the frequency could be pushed as low as 5 GHz. We scale pulsar luminosities to putative search frequencies of 5 GHz, 10 GHz, or 15 GHz assuming a power-law spectrum with spectral index \( -1.8 \) (Maron et al. 2000), and give observability results for each case.

The minimum flux detectable at a telescope can be estimated with the following equation in Lorimer & Kramer (2005, hereafter LK), originally from Dewey et al. (1985):

\[
S_{\text{sys}} = \frac{(\text{SNR}_{\text{min}})\beta_0 S_{\text{sys}}}{\sqrt{n_p f_{\text{obs}} \Delta f}} \sqrt{\frac{W}{P-W}}.
\]

Here \( W \) and \( P \) are, respectively, the pulsar pulse width and period. From our assumption that \( W/P \) is 5% we get \( \sqrt{W/(P-W)} = 0.23 \). The parameter \( \beta_0 \) is a correction factor for imperfections in data collection. Most current pulsar detection systems are multibit systems with \( \beta_0 \) close to 1, and this is the value we shall use. For \( n_p \), the number of polarizations recorded and summed in the detection process, we will use \( n_p = 2 \) because typically two polarizations are summed during pulsar detection scans. SNR\text{_{min}} is the minimum detectable signal-to-noise ratio required in a search; we will take this to be 8.

For the time pointed at the source, \( t_{\text{obs}} \), we will assume a 1 hr observing time. The bandwidth of the recorded data \( \Delta f \) depends highly on the pulsar detection instruments used at a particular telescope. Bandwidths at the frequencies in which we are interested typically range from 500 MHz to 3 GHz. \( S_{\text{sys}} \) is the system equivalent flux density, which depends strongly on the collecting area of the telescope and the raw antenna sensitivity (see LK). Table 1 details the relevant characteristics of the current Parkes telescope in Australia and Green Bank Telescope (GBT) in the USA, as well as the planned Square Kilometre Array (SKA).

### 3. PROBABILITY CALCULATIONS

In this section, we show how to calculate the probability that radiation from a single pulsar is detectable by a telescope on Earth, after having passed through the strong-field region of the black hole. This calculation naturally breaks down into two parts: determining what orientations of the pulsar and black hole produce strongly bent beams, and determining where the Earth must be positioned relative to the system in order to detect those beams.

In Paper II, it was shown that for any relative position of pulsar, black hole, and Earth, there are a set of directions, called “keyholes,” in which a photon could be emitted from the pulsar, pass around the black hole, and arrive at the Earth. These keyholes are typically within a few Schwarzschild radii of the black hole, so when the pulsar is far (many Schwarzschild radii) from the black hole, we can treat the keyhole as co-located with the black hole; that is, the pulsar beam must sweep across the black hole. The first part of the probability calculation is to determine for what fraction of the pulsar’s orbit it is in a position to illuminate the black hole with its beam.

We view the system from the perspective of the pulsar, so that the black hole traverses the sky of the pulsar along a great circle corresponding to the orbital plane. (This great circle in the pulsar sky does not imply that the pulsar–SMBH distance is constant.) Meanwhile, the pulsar spins about its rotation axis, and emits radiation in a cone offset from that axis: once per pulsar rotation the cone sweeps out an annulus in the sky of the pulsar along a great circle corresponding to the orbital plane. (This great circle in the pulsar sky does not imply that the pulsar–SMBH distance is constant.) Meanwhile, the pulsar spins about its rotation axis, and emits radiation in a cone offset from that axis: once per pulsar rotation the cone sweeps out an annulus in the sky of the pulsar. This is illustrated in Figure 5, where \( \alpha_0, \Delta \alpha, \) and \( \lambda \) have the meaning described in Section 2 and pictured in Figure 2.

With Figure 5(b) we introduce the angle \( \beta \), the total arc length (if any) over which the annulus intersects the orbital plane. When calculating \( \beta \), it is useful to focus on one hemisphere at a time and to label the two edges of the pulsar’s radiation cone. We will define these two edges as \( \alpha_1 = \alpha_0 - \Delta \alpha \) and \( \alpha_2 = \alpha_0 + \Delta \alpha \). We break the calculation of \( \beta \) into three cases, with one case having two subcases. The first case is that in which the orbital plane of the system is never illuminated by the pulsar’s radiation, \( \alpha_2 < \lambda \), as shown in Figure 6. In this...
case, the value of $\beta$ is trivially zero. The second case is the case in which the orbital plane passes between the outer and inner edges of the annulus: $\alpha_1 < \lambda < \alpha_2$. This case has two subcases. In the first subcase, that for $\alpha_2 > \pi/2$, the entire orbital plane is illuminated by the pulsar, as shown in Figure 7(a). The value of $\beta$ in this case is the entire range $\pi$ that lies in that hemisphere of the pulsar's sky. (Remember that we are assuming symmetric emission about the pulsar's rotational plane, so that the two beams together illuminate the full $2\pi$ range of the orbital plane.) The second subcase, when $\alpha_2 \leq \pi/2$, has the outer edge of the annulus intersecting the orbital plane twice, as shown in Figure 7(b). In this case, $\beta$ can be found from the spherical triangle version of Pythagoras's theorem, applied to the triangle with hypotenuse $\alpha_2$ and sides $\lambda$ and $\beta/2$: $\cos \alpha_2 = \cos \lambda \cos \beta/2$, whence $\beta = 2 \arccos(\cos \alpha_2 / \cos \lambda)$. The final case has both the outer and inner edges of the annulus crossing the orbital plane, $\alpha_1 > \lambda$, as illustrated in Figure 8. The calculation proceeds as in the previous case, but considers only the range of $\beta$ between the triangles with hypotenuses $\alpha_2$ and $\alpha_1$: $\beta = 2 \arccos(\cos \alpha_2 / \cos \lambda) - 2 \arccos(\cos \alpha_1 / \cos \lambda)$. The cases and calculations for $\beta$ are summarized in Table 2.

The determination of this range is shown in Figure 9 for the case $r_0 = 100M$. This figure shows the dramatic amplification at $\phi_{\text{out}} = \pi$, corresponding to strong lensing. For $\phi_{\text{out}}$ slightly less than $\pi$, the attenuation factor is unity, and the bending is not significant. There is bending for $\phi_{\text{out}} < \pi$, but the range of $\phi_{\text{out}}$ for which there is significant bending is small. Moreover,
this range is even smaller than in Figure 9 for the larger, more relevant values of $r_0/M$. As a convenient approximation, therefore, we will consider “strong bending” only for $\phi_{\text{out}} \geq \pi$. The figure shows that as $\phi_{\text{out}}$ increases beyond $\pi$ the attenuation becomes greater and greater.

Our approach will be to specify a radius of emission $r_0$ and a minimum acceptable value of $I/I_0$. From a calculation like that shown in Figure 9 we then find the value of the angle $\delta$, the value of $\phi_{\text{out}} - \pi$ at which the attenuation is that of the minimum acceptable value of $I/I_0$. This value of $\delta$ determines the range of directions in which the Earth must be located if an Earth telescope is to detect the beam: the Earth must lie no more than an angle $\delta$ from the pulsar–black-hole axis.

The corresponding region on the pulsar sky is illustrated in Figure 5(b). Since $\delta$ is typically very small, we can express this area using a flat-space approximation: $2\beta \delta + \pi\delta^2$. The probability that observers on Earth can detect strongly bent beams from a given pulsar is given by the size of this area over the angular area of one hemisphere (again, we assume symmetry across the rotation plane of the pulsar):

$$P_1 = \frac{2\beta \delta + \pi\delta^2}{2\pi}.$$  \hfill (5)

This of course assumes nonzero $\beta$: if $\beta = 0$, the black hole is not illuminated by the pulsar, and there are no strongly bent beams, so $P_1 = 0$. Note that $\beta$ is a function of the underlying parameters $\lambda$, $\alpha_0$, and $\Delta \alpha$, and $\delta$ is a function of the underlying parameters $r_0/M$ and $I_{\text{min}}/I_0$.

### 4. RESULTS

Now that we have shown how to calculate the probability of Earth-based detection of a particular pulsar, we will describe how we estimated the number of pulsars that would be detected given assumptions about the distributions of pulsar characteristics. We ran Monte Carlo simulations that selected $\lambda$ from a uniform distribution of $\cos \lambda$, so that the direction of the pulsar spin axis was uniformly distributed over the sky; similarly, $\alpha_0$ was chosen from a uniform distribution of $\cos \alpha_0$. Then a value for the pulsar’s flux, $S$, was chosen from the distribution shown in Figure 4. Lastly, a value of $r_0/M$ was chosen from the distribution in Equation (1); we cut this distribution off at $r_0/M = 400,000$ since pulsars beyond that point contribute little to the total probability (see below).

The simulations took the pulsar parameters ($r_0$, $S$) chosen by the Monte Carlo method. From these a determination of the minimum value of $I/I_0$ was made (equivalently $S_{\text{min}}/S$) that can be detected for those pulsar parameters. From $I/I_0$ and $r_0$, the value of $\delta$ was determined. The value of $\beta$ was determined through the calculations described in the previous section applied to the values of $\lambda$ and $\alpha_0$ chosen by the Monte Carlo method. The justification for using $\Delta \alpha = 9^\circ$ has been explained in Section 2. $P_1$ was then calculated with Equation (5). This gives us the probability that a single pulsar’s beam will explore the black hole’s strong gravitational field and still be detectable once it reaches the Earth. Monte Carlo simulations were repeated to ensure that results were consistent to better than 1%. We then multiplied our result by the total number of pulsars out to $r_0 = 400,000$, according to the Pfahl and Loeb distribution of Equation (1). The result is the total number of pulsars ($P_{\text{tot}}$) that will, at some point in their orbit about the central SMBH, both illuminate the strong gravitational field and be detectable at Earth. Table 3 gives this number for the three telescopes considered in Section 2, in three different frequency bands, for the two luminosity distributions ATNF and FGK.

The number of pulsars that are observable at some point in their orbit is not directly relevant if the orbital time is much larger than the duration of an observing program. For this reason we introduce a more useful number, the “observability,” $P_{\text{obs}}$, to describe the expected number of pulsars detectable in a limited-time observing program. In order to calculate this

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Table 2

| Case | Condition | $\beta$ Calculation |
|------|-----------|---------------------|
| 1    | $\alpha_2 \leq \lambda$ | $\beta = 0$ |
| 2a   | $\alpha_1 \leq \lambda < \alpha_2$ | $\alpha_2 \geq \pi/2$ |
| 2b   | $\alpha_1 \leq \lambda < \alpha_2$ | $\alpha_2 < \pi/2$ |
| 3    | $\lambda < \alpha_1$ | $\beta = 2 \arccos \left( \frac{\cos \alpha_1}{\cos \lambda} \right)$ |

Table 3

| Telescope Name | Frequency Band | $S_{\text{min}}$ (mJy) | $P_{\text{ATNF}}$ | $P_{\text{FGK}}$ |
|----------------|---------------|-------------------------|-------------------|-------------------|
| Parkes         | C band        | 0.42                    | 8.21              | 0.189             |
|                | X band        | 0.45                    | 3.53              | 0.0490            |
|                | K band        | 0.14                    | 0.839             | 0.00548           |
| GBT            | C band        | 0.0039                  | 27.0              | 1.45              |
|                | X band        | 0.0066                  | 11.5              | 0.331             |
|                | K band        | 0.0066                  | 7.61              | 0.167             |
| SKA            | C band        | 0.00007                 | 113               | 16.6              |
|                | X band        | 0.00006                 | 79.1              | 9.58              |
|                | K band        | 0.00005                 | 65.7              | 7.05              |

Figure 9. Intensity ratio $I/I_0$ as a function of $\phi_{\text{out}}$, for $r_0 = 100 M$. The shaded regions show the ranges of $\phi_{\text{out}}$ that are not of interest either because the pulsar beam is too weakly deflected or because it is too strongly attenuated.

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number, we ran the Monte Carlo simulations with a specified observational program duration \( L \). Once \( P_1 \) was calculated, we then compared the pulsar’s orbital period \( T \) to \( L \). If \( T \) was less than or equal to \( L \), then \( P_{\text{obs}} \) was taken to be \( P_1 \). If \( T \) was greater than \( L \), then \( P_1 \) was replaced by
\[
P_{\text{obs}} = \frac{P_1 \times L}{T}, \tag{6}
\]
and the result was multiplied by the total number of pulsars. Figure 10 shows the results of the Monte Carlo simulations for observational program durations ranging from one year to seven years.

Figure 11 shows the variation in the number of pulsars detected, for \( S_{\text{min}} = 0.0066 \) mJy at 5 GHz, as the cutoff radius is changed, and justifies our use of the cutoff at \( r_0/M = 4 \times 10^5 \).

Other values of \( S_{\text{min}} \) and observing frequency give similar results.

5. OBSERVING PROGRAMS AND STRATEGIES

A natural first question about observing strongly deflected beams is “how will we know that they are strongly deflected?” The answer starts with the fact that the angle through which the beam is “strongly” deflected is not large. For our paradigmatic case, \( r_0 = 10^4 M \), the bending is approximately 0.036 rad. For larger \( r_0 \) the deflection, for a given \( S_{\text{min}} \), is even smaller.

Since the “strong” deflection is small, we will receive a deflected beam only when the emitting pulsar, the SMBH, and the Earth are almost on a straight line. Since pulsar beam widths are large compared to the deflection, this means that if the Earth receives the deflected beam, it will also receive the direct beam. The geometry of the direct and deflected beams is shown in
Figure 11. Number of pulsars expected, for $S_{\text{min}} = 0.0066$ mJy, at 5 GHz as a function of the cutoff $r_0/M$ for the distribution in Equation (1) and the ATNF luminosity distribution. Each curve is labeled with the number of years assumed for the search.

Figure 12. Geometry of the observation of direct and deflected beams.

Figure 13. Flat spacetime propagation from large radius to very large radius. Angles $\phi_{\text{in}}$, for the large and the very large emission radius are distinguished with the superscripts $(R_0)$ and $(r_0)$, respectively.

6. CONCLUSIONS

Our estimates suggest that a multiyear program that monitors Sgr A* with radio observations for 1 hr every other day has a very small but non-negligible probability of detecting pulsar beams that have been strongly deflected by our Galaxy’s SMBH. With instruments coming in the near future, in particular the SKA, the probability should become high enough so that a three-year observational program might optimistically detect such beams from multiple pulsars, or, in the absence of detections, would constrain the more optimistic models for the pulsar population in the Galactic cusp.

Our estimates in this paper constitute a first step in the study of probabilities of detection of a strongly deflected beam. The intention was to establish whether the probabilities are so small that observations are out of the question, or so large that
current observations rule out models, like that of Pfahl & Loeb (2004), with a significant density of pulsars in Sgr A*. The estimates in this paper establish neither extreme: a concerted observing program with the best current telescopes would not be guaranteed to make a detection, but under optimistic models or with improved instruments could plausibly detect strongly bent beams from a (small) number of pulsars. This provides motivation for such a program and also for further study of the problem of pulsar beam deflection by SMBHs.

Such an improved study would have to include effects of spin of the SMBH, and of eccentricity of orbits. While our approach of using averages and simple assumptions was appropriate for the purpose of this paper, effects due to SMBH spin, and of eccentricity of orbits, could increase the parameter space of pulsar configurations whose beams can reach the Earth. Such work is now underway.

The most exciting result of these preliminary estimates is their indication that we are potentially on the verge of detecting a new phenomenon: pulsar beams that have passed through the strong-field region of the SMBH at the center of our Galaxy, beams that can bring us information about the properties of the SMBH and its surrounding spacetime might be inaccessible in any other way.

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APPENDIX

We are primarily interested in values of $\phi_m$ that are only slightly smaller than $\pi$. In this case the photon path starting at some very large radius will penetrate to small radii, and almost all the bending will take place at small radii. We can then find some very large radius will penetrate to small radii, and almost

\[ F(\phi; r) = \phi + F\left(\sin^{-1}\left(\frac{r_0}{R_0} \sin \phi\right); R_0\right) - \sin^{-1}\left(\frac{r_0}{R_0} \sin \phi\right). \]

Thus, knowing the $F$ function for any (sufficiently large) $R_0$, we can evaluate it for any larger $r_0$, and thus determine the maximum deflection angle $\delta$ via Equation (3). Figure 14 shows our reference bending function for a radius $R_0 = 100 M$.

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Figure 14. Bending function $\phi_{\text{out}} = F(\phi_{\text{in}})$ for bending angles near $\pi$, for an initial radius $R_0 = 100 M$.

From a combination of Equations (A1) and (A3), written in terms of the function $F(\phi; r)$, the full expression can be given as

$$F(\phi; r_0) = \phi + F\left(\sin^{-1}\left(\frac{r_0}{R_0} \sin \phi\right); R_0\right) - \sin^{-1}\left(\frac{r_0}{R_0} \sin \phi\right).$$

We next note that $\phi_{\text{out}}$ for the photon starting at $R_0$ is less than $\phi_{\text{out}}$ for that same photon world line considered to start at $r_0$, in flat space, according to

$$\phi_{\text{out}}^{(r_0)} = \phi_{\text{out}} + \gamma.$$