Detecting the Orbital Motion of Nearby Supermassive Black Hole Binaries with \textit{Gaia}

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We show that a 10 year \textit{Gaia} mission could astrometrically detect the orbital motion of $\sim 1$ sub-parsec separation supermassive black hole binary in the heart of nearby, bright active galactic nuclei (AGN). Candidate AGN lie out to a redshift of $z = 0.02$ and in the V-band magnitude range $10 \lesssim m_V \lesssim 13$. The distribution of detectable binary masses peaks at a few times $10^7 M_\odot$ and is truncated above a few times $10^8 M_\odot$.

I. INTRODUCTION

The \textit{Gaia} satellite is mapping the positions of the stars with unprecedented precision. Its 5 year mission: to survey the 6D phase space coordinates of a billion stars to an astrometric unprecedented precision. Its 5 year mission: to survey the distant and powerful sources of multi-wavelength emission.

We consider the case where only one SBH in the SBHB is luminous [e.g., Ref. 50]. Over the course of an orbit, the position of the SBH, and thus the center of light, changes by a little proper motion or parallax. Despite this expectation, \textit{Gaia} has detected $\geq 1\text{mas}$ offsets in optical and radio positions of AGN, probing dislodged AGN or radio/optical jet properties [5–8]. In this Letter we show that on $\lesssim 50\mu\text{as}$ scales, this expectation is also relevant for AGN that harbor sub-parsec (pc) separation SBH binaries (SBHBs). Orbital motion of one or both accreting SBHs in a SBHB can change the position of the optical emitting region of the AGN by an angle greater than the astrometric precision of \textit{Gaia}. SBHB orbital motion would be distinct from the linear motion expected for a jet or ejected AGN. Because binary-induced motions will only occur for a minority of AGN, there will be little impact on \textit{Gaia}'s calibration. This observation does, however, present a path towards definitive detections of sub-pc separation SBHBs.

While solid lines of evidence lead us to expect that SBHBs reside in the centers of some galaxies [9], their definitive detection at sub-pc separations is yet to be obtained. The existence of sub-pc SBHBs is of special importance as it embodies the ‘final-parsec problem’ [9, 10], determining the fate of SBHBs. If interaction with the environments in galactic nuclei can drive SBHBs to sub-pc separations, then they will merge via emission of gravitational waves (GWs), detectable out to redshift $z \geq 10$ by the future space-based GW observatory LISA [11], and generating a low-frequency stochastic GW background detectable by the Pulsar Timing Arrays (PTAs; 12).

To determine which, if any, proposed mechanisms, [e.g., 13–18], solve the final-parsec problem in nature, one must characterize a population of sub-pc SBHBs. Current detection methods are indirect and require campaigns that last many years [e.g., 19–48]. While these techniques provide a way towards identifying and vetting SBHB candidates via a combination of indirect methods, a more direct approach is desired.

Recently, we have shown that mm-wavelength VLBI possesses the astrometric resolution and longevity to repeatedly image SBHB orbits out to redshift $z \sim 0.5$, providing direct evidence for SBHBs in radio-loud AGN [49]. The technique that we propose here also directly tracks the SBHB orbit with the advantage that target AGN need not be bright in mm-wavelengths and that unlike VLBI, \textit{Gaia} is conducting a survey mission that will map the entire sky, and, as we show, could find evidence for SBHBs within the next 5 – 10 years.

II. HOW MANY SBHBS COULD \textit{GAIA} DETECT?

The angular scale of nearby sub-pc separation SBHBs is $\mathcal{O}(10)\mu\text{as}$. The diffraction-limited imaging resolution of \textit{Gaia} is $\sim 10^3$ times larger. While \textit{Gaia} cannot image sub-pc separation SBHBs, it does possess the astrometric precision to detect $\sim 10\mu\text{as}$ centroid shifts in bright sources.

We consider the case where only one SBH in the SBHB is luminous [e.g., Ref. 50]. Over the course of an orbit, the position of the SBH, and thus the center of light, changes by a characteristic value given by the semi-major axis of the binary, $a$ (see §III B for further discussion). At angular-diameter distance $D_A(z)$, the orbital angular extent is $\theta_{\text{orb}} \approx a/D_A(z)$. \textit{Gaia} can detect orbital motion if $\theta_{\text{orb}}$ is greater than its astrometric precision, and if the orbital period is shorter than twice the mission lifetime.

\textit{Gaia}'s astrometric resolution can be parameterized by the brightness and color of the source. Working in Johnson V-band magnitudes, we adopt an average AGN $V - I_c = 0.7$ based on the $r - i$ colors of nearby ($z \leq 2.1$) SDSS AGN [51], and color correction equations [52], that yield a $V - I_c$ range of 0.3 – 1.1. We use the fitting formula from Eqs. (4-7) of Ref. [2] and the \textit{Gaia} G-band to V-band conversion [53] to compute the V-band magnitude-dependent astrometric resolution of \textit{Gaia}. The astrometric end-of-mission resolution, $\sigma_{\text{res,n}}$, is $9\mu\text{as}$ for a $m_V = 13$ AGN [4]. This corresponds to a physical separation of $\sim 0.01$ pc at a distance of 200 Mpc, suggesting that \textit{Gaia} can probe sub-pc, GW-driven SBHBs if they reside in bright AGN.

Multiple works have considered exoplanet detection with \textit{Gaia} [54–58]. We draw on this body of work which shows that the relevant quantity to consider for astrometric orbital detection is the signal-to-noise ratio, $\text{SNR} = \theta_{\text{orb}}/\sigma_{\text{single}}$, where $\sigma_{\text{single}}$ is the precision for a single scan which we compute.

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as $\sigma_{\text{angle}} = \sqrt{70}/(2.15 \times 1.2)\sigma_{\text{com}}$, the 5-yr end-of-mission astrometric precision multiplied by the sky-position-averaged number of scans per source (over 5 yrs) and geometric sky averaging factors [57]. As shown in Ref. [58], an SNR of 2.3 (1.7) is required to achieve a 50/50 detection rate for a 5-yr (10-yr) Gaia mission, with a false-positive rate estimated to be $\lesssim 10^{-4}$. Hence in this work we adopt a minimum SNR = 2 corresponding to a minimum detectable orbital angular size of $\theta_{\text{min}} = 2\sigma_{\text{angle}}$. Next we compute the expected number of such Gaia-detectable SBHBs for both a 5-yr mission and an extended 10-yr mission.

### A. Calculation

We use the quasar luminosity function [QLF; 59] to derive the number of AGN per redshift $z$ and luminosity $L$. From $L$ and $z$, and a bolometric correction to the V-band of 10 [60], we find the corresponding V-band magnitude $m_V(L,z)$, which gives the astrometric resolution, $\theta_{\text{min}}$. Combined with the redshift, this yields the minimum binary separation that Gaia can detect in that luminosity and redshift bin. At each luminosity bin we derive a total binary mass from the assumption that the AGN emits at a fraction of Eddington luminosity, $L = f_{\text{Edd}}L_{\text{Edd}}(M)$. The minimum binary separation and the binary mass yield the minimum binary orbital period for which Gaia could detect orbital motion,

$$P_{\text{min}}(L,z) = \frac{2\pi \left[\theta_{\text{min}}(L,z)D_A(z)\right]^{3/2}}{\sqrt{GM(L,f_{\text{Edd}})}}. \tag{1}$$

We adopt $f_{\text{Edd}} = 0.1$, motivated by an average value for bright AGN [61, 62].

We additionally require that the binary complete at least one orbit over the course of the Gaia mission. Otherwise orbital motion is difficult to detect [58] or could be confused with linear motion. The combined requirements constrain $P_{\text{min}}(L,z)$ to be less than a maximum time period $P_{\text{max}} = 10$ yrs (5 yrs) for a 10-yr (5-yr) Gaia mission. We call AGN for which $P_{\text{min}}(L,z) \leq P_{\text{max}}$ `Gaia targets’. This estimate, however, does not account for the probability that an AGN harbors a SBHB at the desired orbital period. To estimate this, we assume that a fraction $f_{\text{bin}}$ of all AGN are triggered by SBHBs. We then use the quasar lifetime $t_Q$ and the residence time of a SBHB at orbital period $P$ to compute the fraction of $t_Q$ that a binary spends at orbital periods below $P$ [see, e.g., 29, 49]. The residence time due to GW emission is,

$$t_{\text{res}} = \frac{a}{a} = \frac{20}{256} \left(\frac{P}{2\pi}\right)^{8/3} \left(\frac{GM}{c^3}\right)^{-5/3} q_s^{-1}, \tag{2}$$

for binary symmetric mass ratio $q_s = 4q/(1 + q)^2$, where $q = M_2/M_1 \leq 1$ and $M_1 + M_2 = M$. The probability for observing the binary at orbital periods $P \leq P_{\text{bin}}$ is given by $F(P,M,Q)$ or $\min [t_{\text{res}}(P,M,q_s)/t_Q,1]$. We evaluate the residence time at $P_{\text{min}}$.

The total number of Gaia-detectable SBHBs is,

$$N_{\text{SBHB}} = f_{\text{bin}} \int_0^\infty \left\{4\pi d^2/dz d^2 N/d log L dV \int_0^{\log L_{\text{min}}(z)} \frac{d^2 N}{d log L dV} F(P,M,Q) \right\} d log L dz, \tag{3}$$

where $d^2 N/d log L dV$ is the pure-luminosity-evolution, double-power-law QLF with redshift dependent slopes from Ref. [59] (last row of Table 3 labeled ‘Full’). $d^2 V/dz d\Omega$ is the co-moving volume per redshift and solid angle [63], $H$ denotes the Heaviside function, $m_V(\log L_{\text{min}}(z), z)$, and we choose a fiducial quasar lifetime $t_Q = 10^7$ yrs [49, 64].

### B. Results

Table I lists parameter choices and the resulting total number of Gaia-detectable SBHBs. For fiducial values, and a 10-yr Gaia mission, $N_{\text{SBHB}} \approx 11 f_{\text{bin}}$. Thus, if the fraction of SBHBs in local bright AGN is $f_{\text{bin}} \gtrsim 0.1$, Gaia has the potential to find an SBHB during an extended, 10-yr lifetime. Previous studies have argued for a similar value of $f_{\text{bin}}$ (typically 10%, which is our fiducial value) based upon periodic variability searches in AGN [31, 34].

Table I also lists our ‘optimistic’ and ‘pessimistic’ parameter choices. In the optimistic case, $N_{\text{SBHB}} \approx 13 f_{\text{bin}}$ SBHBs. In the pessimistic case, $N_{\text{SBHB}} \approx 8 f_{\text{bin}}$ SBHBs. For each case we also consider the benefit of 20 years of observation (while Gaia cannot last that long, another 10 years of a successor mission could fulfill this in the future [e.g., Ref. 66]).

| Parameter | Meaning | Fiducial | Optimistic | Pessimistic |
|-----------|---------|----------|------------|------------|
| $f_{\text{bin}}$ | The fraction of AGN harboring SBHBs | 0.1 | * | * |
| $f_{\text{Edd}}$ | The Eddington fraction of bright AGN | 0.1 | * | * |
| BC | Bolometric correction from V-band | 10.0 | * | * |
| $t_Q$ | The AGN lifetime | 10$^7$ yrs | 5 x 10$^6$ yrs | 10$^6$ yrs |
| $V - I_c$ | A mean color for nearby AGN | 0.7 | 1.1 | 0.0 |
| $P_{\text{max}}$ | Mission lifetime | 10 yrs (5 yrs) (20 yrs) | 10 yrs (5 yrs) (20 yrs) | 10 yrs (5 yrs) (20 yrs) |
| $q$ | Binary mass ratio | 0.1 | 0.05 | 1.0 |

$N_{\text{SBHB}}$ Number of detectable (SNR $\geq 2$) SBHBs | 1.1 (0.3) | 1.3 (0.4) | 0.8 (0.2) |

Table I. Model parameters and the resulting number of Gaia-detectable SBHBs (note that a 20 year mission lifetime requires a successor to Gaia).
Such an extended mission could result in up to $38 f_{\text{bin}}$ putative SMBHB detections.

Figure 1 plots distributions of Gaia SBHB candidates vs. V-band magnitude, redshift, and binary mass. We show: (i) the total number of AGN found from integrating the QLF (black-dotted line); (ii) the number of ‘Gaia-target’ AGN, (teal-dashed line); (iii) ‘binary-targets’, including the probability $\mathcal{F}(M, P, q_s)$ for an AGN to contain a binary at the desired orbital period (orange line); and (iv) the binary-targets with SNR $\geq 2$, for which $\geq 50\%$ of the population will be detectable with a $\leq 10^{-4}$ false-positive rate. The teal and solid-orange lines (ii and iii) are drawn for SNR $\geq 1$ in order to more easily discuss the target population discussed below and to compare to the SNR $\geq 2$ case. Integration under the dashed-orange lines and multiplication by $f_{\text{bin}}$ yields $N_{\text{SBHB}}$ in Table I. For reference, the gray histograms show the observed distribution of nearby AGN with $m_V < 16$ [65]. Note, however, that magnitudes relevant for our study are those of the central point source, presumably generated by accretion onto either component of a putative binary, whereas magnitudes from Véron-Cetty and Véron [65] can include also the extended host galaxy for such nearby systems. Hence the Véron-Cetty and Véron [65] catalog may overestimate the number of nearby bright systems in the context of this work.

The left panel of Figure 1 displays the number of SBHBs per AGN V-band magnitude. Comparing the teal-dashed line labeled ‘Gaia target’ and the black-dotted line (All AGN), we see that the orbital period cut $P_{\text{min}} \leq P_{\text{max}}$ removes AGN with $m_V \geq 12.5$. This is because Gaia’s resolution worsens for dimmer targets. To illustrate this, the purple dot-dashed line plotted on the right vertical axis of the left panel shows Gaia’s single-scan astrometric precision vs. $m_V$.

Comparison of the dashed-teal line with the solid-orange line shows that brighter AGN in the ‘Gaia target’ distribution are less likely to harbor a SBHB at the required orbital period $P_{\text{min}}$. This is because nearby, bright AGN correspond to more luminous AGN which correspond to AGN with higher binary masses via the Eddington relation. At a fixed orbital period, higher mass binaries inspiral more quickly and are hence less likely to be found. Where the teal and orange curves overlap is where the binary residence time is at least the quasar lifetime.

The dashed-orange line for SNR $\geq 2$ binaries effectively represents a population with a larger minimum orbital period. Hence there are fewer such binaries that lie between this minimum and $P_{\text{max}}$. The dashed-orange line is higher than the solid-orange line at bright magnitudes because the probability $\mathcal{F}$ is larger due to a longer minimum orbital period. The dashed-orange line shows that for the fiducial case, the detectable SBHB distribution peaks at $m_V = 12$, with an expectation value greater than $1 f_{\text{bin}}$ for AGN with $10.3 \leq m_V \leq 13$.

The middle panel of Figure 1 displays the redshift distribution of Gaia-detectable SBHBs. The maximum-orbital-period cut removes candidate AGN at all redshifts, while the binary-target distribution is reduced in number from the Gaia-target distribution at higher redshifts. The latter is because SBHBs at higher redshift must be more luminous in order for Gaia to resolve orbital motion. Again, more luminous AGN are associated with more massive SBHBs which merge more quickly. The SNR $\geq 2$ binaries (dashed-orange line) have a log $z$ distribution peaking at $z \sim 0.01$ with expectation value $\geq 1 f_{\text{bin}}$ for $z \leq 0.02$.

The right panel of Figure 1 displays the distribution in binary mass of Gaia-detectable SBHBs. Comparison of the black-dotted and teal-dashed lines shows that the highest fraction of AGN are removed from the Gaia-target distribution at lower binary masses. This is because SBHBs with lower masses have much longer orbital periods for the same angular separation and redshift. Again, the comparison of the solid-orange and teal-dashed lines shows that the expectation value for the number of Gaia-detectable SBHBs also decreases for more massive binaries. For fiducial parameter values, the SNR $\geq 2$ binaries distribute in $\log M$ with a peak at $M \sim 3 \times 10^7$ and expectation value $\geq 1 f_{\text{bin}}$ for $M \leq 3 \times 10^8 M_\odot$.

For optimistic (pessimistic) parameter values (Table I), the distributions peak at nearly the same magnitudes with a similar though slightly increased (decreased) range, and extends to higher (lower) redshifts $z \leq 0.02$ ($z \geq 0.01$), and higher (lower) binary masses $M \leq 5 \times 10^7 M_\odot$ ($M \geq 8 \times 10^7 M_\odot$).
For a shorter, 5-year mission lifetime, the SNR $\geq 2$ population peaks at a slightly dimmer $m_V \sim 11$ and has expectation value $\geq 1/f_{\text{bin}}$ for $10.4 \leq m_V \leq 12$, $z \leq 0.01$, and $M \leq 4 \times 10^7 M_\odot$.

Cumulative distributions of SNR $\geq 2$ binary targets in orbital period and orbital velocity are plotted in Figure 2. The period distribution (blue) shows the fraction of Gaia-detectable SBHBs as a function of $P_{\text{max}}$. We note that, while we assume a constant 5-yr mission-end resolution, this may change over the course of a longer mission due to better PSF fitting, abut also due to possible instrument degradation. The linear dependence of the period distribution indicates that the period restriction $P_{\text{min}} < P_{\text{max}}$ dominates over the steeper $t_{\text{res}} \propto P^{8/3}$ residence-time dependence.

The velocity distribution (red) shows the number of Gaia-detectable SBHBs with orbital velocity $v_{\text{orb}}/c$ above velocity $v/c$. This quantity sets the fractional amplitude of photometric modulations caused by the relativistic Doppler boost, given by $\Delta F_v/F_v \approx (3 - \alpha_v)v_{\text{orb}}/c \cos I$, for specific flux $F_v$, $v_{\text{orb}}/c < 1$, inclination of the orbital plane to the line of sight $I$, and frequency-dependent spectral slope $\alpha_v$ [with typical values $-2 \lesssim \alpha_v \lesssim 2$; see Refs. 50, 67]. We compute $v_{\text{orb}}/c$ as that of the secondary with $q = 0.1$.

Figure 2 shows that Gaia-detectable SBHBs will have $v_{\text{orb}}/c \lesssim 0.03$. Hence, for $\alpha_v = -2$, Doppler-induced modulations will have $\Delta F_v/F_v \lesssim 5\%$, translating to $\Delta m_V \lesssim 0.05$ mag amplitude modulations. Gaia’s photometric precision is better than 0.01 mag at $m_V \lesssim 14$ [3, 68] and could identify Doppler modulation coincident with astrometric shifts of AGN optical regions. However, at $\sim$year timescales, intrinsic AGN variability has often a higher amplitude than the maximum $\Delta m_V = 0.05$ mag Doppler signal predicted here [69], and finding this signal without a Gaia detection would be difficult. If Gaia identifies a SBHB candidate and its orbital period astrometrically, then a targeted search for periodicity at the identified orbital period, as well as further photometric monitoring beyond the lifespan of Gaia, could identify Doppler modulations, further validating the SBHB interpretation.

III. DISCUSSION

Binary motion can be uniquely identified and disentangled from linear motion. Orbital motion in AGN would not be mistaken for a stellar binary because of the much shorter orbital periods associated with more massive SBHBs at the measured orbital separation. Moreover, Gaia measures high-resolution spectra of objects with $V \leq 15.5$ [2], implying that AGN can be identified unambiguously. Additionally, because Gaia will observe each bright object on the sky a median of 72 times [for the 5-yr mission; 2], candidate AGN spectra could be monitored for broad-line variations hypothesized to accompany SBHBs [e.g., 28], though Gaia’s spectral resolution may not be sufficient to detect such broad-line shifts and variations. Broad-line monitoring from Gaia or ground based spectroscopic measurements along with multi-wavelength photometric monitoring for binary-induced periodicity [e.g., 31, 34–36, 50, 70] could be used in tandem with Gaia orbital tracking to prove the existence of sub-pc separation SBHBs, and build a SBHB identification ladder by studying the characteristics of confirmed SBHB-harboring AGN.

Because we predict the Gaia-detectable SBHBs to lie in nearby, bright AGN, future work should examine these known sources. Those exhibiting, e.g., periodic variability should be given priority for examination in the Gaia dataset. If any Gaia SBHB candidates are radio-loud, they can be targeted by mm-VLBI observatories that could simultaneously track the orbital motion [49], allowing orbital tracking beyond the lifetime of Gaia and offering insight into the relation between radio and optical emission generated by SBHBs. Additionally, SBHB orbital tracking can yield precise binary mass measurements, or even a novel measurement of the Hubble constant [49].

A. Gravitational Waves

The SBHBs detectable by Gaia would be emitting GWs in the PTA frequency band. As a consistency check, we follow Ref. [49] and use the QLF to compute the corresponding stochastic GW background (GWB). For simplicity and in difference from Ref. [49], we assume that the SBHBs are driven together only by GW radiation and that $f_{\text{Edd}} = 0.1$. The resulting GWB falls a factor of a few below the current PTA limits, consistent with previous studies [e.g., 71].

The most massive and nearby Gaia-detectable SBHBs, have $M \sim 10^{8.5} M_\odot$ and $z \sim 0.01$ (Figure 1). Such an SBHB, with a mass ratio of unity and an orbital period of less than 3 years, could be resolved as an individual source with a $\sim 13$ year PTA observation. Determination of the orbital parameters and location on the sky by Gaia could aid PTA detection.
B. Caveats

Throughout we have assumed that only one SBH is bright and that the light centroid of the system moves a characteristic distance given by the orbital semi-major axis. Depending on the relative masses and luminosities of the two SBHs, however, this distance can vary. The motion of the light centroid can be discerned from the difference between the fixed center of mass of the binary and the center of light. Defining the distance given by the orbital semi-major axis. Depending on the relative masses and luminosities of the two SBHs, how-


dependently, our calculation relies on the unknown rate at which gas-driven decay does not affect our result when occurring at less than the Eddington rate. Furthermore, the binaries could stall before they make it to the small separations considered here, in that case our binary probability prescription is invalid and neither Gaia nor any other technique will find very compact SBHBs. However, detection of a SBHB with Gaia could rule out that possibility.

Since a detection of SBHBs would be the first of its kind, one may ask if the SNR cut that we adopt from [58], originally intended for astrometric planet detection, yields a higher false-positive rate than desired for such a task. Considering that there are only \( \sim 10^3 \) bright nearby AGN for which this detection method could be employed (e.g. Figure 1), and that the 50\% detection rate is computed using a detection criterion that was shown by Ranalli et al. [58] to yield a \( \lesssim 10^{-4} \) false-positive rate, we view this as an acceptable minimum criteria for motivating the possibility of SBHB orbital tracking.

We finally note, that the number of SBHBs with orbital separation larger than the end-of-mission precision and \( P_{\text{max}} \lesssim 20 \) yrs is large, \( \approx 440 f_{\text{bin}} \). Such systems would move by an orbital separation that is resolvable by Gaia over its lifetime, but not necessarily resolved by the single-scan precision for each of Gaia’s \( \sim 70 \) observations. While not offering a definitive detection of a SBHB, such anomalous astrometric measurements of AGN light centroids should be flagged for further investigation.

IV. CONCLUSION

We have shown that a 10 yr Gaia mission has the capability to astrometrically track the orbital motion of \( O(1) \) SBHBs in bright \( (m_V \lesssim 13) \), nearby \( (z \lesssim 0.02) \) AGN. The discovery of SBHB orbital motion over the next few years of the Gaia mission would open a new field of SBHB demography, generating an enormous boon for our understanding of the mutual growth of SBHs and galaxies, evidence towards resolving the final-parsec problem, the prospect of sources of gravitational waves for PTAs, and a new method for calibrating cosmological distances [49]. There is a strong incentive to analyze astrometric data of bright, nearby AGN from Gaia DR2 and onwards for signatures of SBHB orbital motion.

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