Detection of radial velocity shifts due to black hole binaries near merger

B. McKernan\textsuperscript{1,2,3,4*}, K.E.S. Ford\textsuperscript{1,2,3,4}

\textsuperscript{1}Department of Science, Borough of Manhattan Community College, City University of New York, New York, NY 10007, USA
\textsuperscript{2}Department of Astrophysics, American Museum of Natural History, New York, NY 10024, USA
\textsuperscript{3}Graduate Center, City University of New York, 365 5th Avenue, New York, NY 10016, USA
\textsuperscript{4}Kavli Institute for Theoretical Physics, U. C. Santa Barbara, CA 93106, USA

\section*{ABSTRACT}

The barycenter of a massive black hole binary will lie outside the event horizon of the primary black hole for modest values of mass ratio and binary separation. Analogous to radial velocity shifts in stellar emission lines caused by the tug of planets, the radial velocity of the primary black hole around the barycenter can leave a tell-tale oscillation in the broad component of Fe K\textsubscript{α} emission from accreting gas. Near-future X-ray telescopes such as \textit{Astro-H} and \textit{Athena} will have the energy resolution ($\delta E/E \lesssim 10^{-3}$) to search nearby active galactic nuclei (AGN) for the presence of binaries with mass ratios $q \gtrsim 0.01$, separated by several hundred gravitational radii. The general-relativistic and Lense-Thirring precession of the periapse of the secondary orbit imprints a detectable modulation on the oscillations. The lowest mass binaries in AGN will oscillate many times within typical X-ray exposures, leading to a broadening of the line wings and an over-estimate of black hole spin in these sources. Detection of periodic oscillations in the AGN line centroid energy will reveal a massive black hole binary close to merger and will provide an early warning of gravitational radiation emission.

\textbf{Key words:} galaxies: active – accretion, accretion discs – black hole physics– relativistic processes – techniques: radial velocities

\section*{1 INTRODUCTION}

Galactic nuclei host supermassive black holes ($> 10^6 M_\odot$) (Kormendy & Ho 2013) and should be the sites of mergers of massive black holes (MBH). Binary black holes are expected to arise due to merging supermassive black holes (SMBH) throughout cosmic time in $\Lambda$CDM cosmology (e.g. Springel et al. 2005), as well as due to intermediate mass black hole (IMBH) formation in disks around SMBH (e.g. Levin 2007, McKernan et al. 2012). Possible observational signatures of these merging MBH are important to find (e.g. Milosavljević & Phinney 2003, Bogdanovic et al. 2003, Bode et al. 2010, McKernan et al. 2013, 2014, Roedig et al. 2014, Farris et al. 2014) as the search for binaries probes ever smaller separations (Comerford et al. 2013, Ford et al. 2014, Graham et al. 2013). Here we discuss the possibility of detecting those massive black hole binaries in the local Universe closest to merger, via a radial velocity imprint in the broad FeK\textsubscript{α} line. We demonstrate the effect and its magnitude and we show that near future X-ray telescopes with very fine energy resolution (\textit{Astro-H} and \textit{Athena} with $\delta E/E \lesssim 10^{-3}$ in the FeK band) will be able to detect MBH binaries near merger at mass ratios $q \gtrsim 0.01$ and separations of several hundred gravitational radii.

\section*{2 BINARY BLACK HOLE DYNAMICS}

A binary black hole will orbit its center of mass (barycenter), thereby adding a radial velocity component to line-emitting material immediately surrounding the primary SMBH. This is analogous to radial velocity shifts of stellar spectral lines as the star orbits its barycenter due to planetary tugs (e.g. Ohta, Taruya & Suto 2003). By analogy, we can write the radial velocity component ($v_{\text{rad}}$) of the primary SMBH around the barycenter as (Ohta, Taruya & Suto 2003)

\begin{equation}
    v_{\text{rad}} = \frac{a_b}{\ell} \frac{q}{1 + q} \nu \sin(i)[\sin(f + \omega) + e \sin(\omega)]
\end{equation}

where $q = m_2/M_1$ is the mass ratio of the secondary BH ($m_2$) to the primary BH ($M_1$), $a_b$ is the binary semi-major axis, $\ell^2 = 1 - e^2$ where $e$ is the orbital eccentricity of the

\textit{*} E-mail: bmckernan at amnh.org (BMcK)
secondary, $\nu = 2\pi/T_{\text{oab}}$, is the secondary mean motion or orbital frequency, $i$ is the inclination angle of the binary to the observers’ sight line ($i = 90^\circ$ is edge-on and yields maximal radial velocity components), $f$ is the true anomaly or the angle made by the secondary in its orbit as measured from a line joining the focus and periapsis, and $\omega$ is the argument of periapsis (see e.g. Figs 1 & 2 in Ohta, Tanuya & Suto (2003) for sketches of these orbital parameters). The inner accretion disk is bound to the primary so spectral lines originating in the inner disk will oscillate around their rest centroid energies by $v_{\text{rot}}/c$ on the timescale of the secondary’s orbit (Yu & Lu 2001, Bogdanovic et al. 2009, Sesana et al. 2012). As binary separation shrinks, the disk can become strongly perturbed. In the limit of $a_0$ of a few tens of $r_g$, we should expect the line profile to differ from the simple model below (see e.g. Sesana et al. (2012); McKernan et al. (2005) for sketches of these orbital parameters). The inner disk can become warped (upper; Takahashi et al. (2010)) and the micro-calorimeter planned micro-calorimeter energy resolution for $E_{\text{GR}} \sim 20$–$30r_g$ of the primary and very tight binaries ($a_0$ of tens of $r_g$) will be much rarer than those at wider separations ($a_0$ of a few hundred $r_g$). Even if the line profile is perturbed, the periodic wobble will occur in the manner we outline below and may still be detectable. Eqn. 1 can be rewritten as a energy shift ($\delta E$) in a spectral line centroid energy ($E$) as

$$\delta E = \left(\frac{r_g}{a_b}\right)^{1/2} \frac{q}{1 + q} \frac{\sin(i)}{\ell} \sin(\ell + \varpi) + e \sin(\varpi)$$

where $r_g = G(M_1 + m_2)/c^2$ is the gravitational radius of the binary and $a_b$ is in units of $r_g$. $q_2$ shows the maximum $\delta E/E$ as a function of binary separation and mass ratio from eqn. 1 assuming circular orbits and edge-on inclination. Red horizontal dashed lines in Fig. 1 denote planned micro-calorimeter energy resolution for Astro-H (upper: Takahashi et al. 2010) and the micro-calorimeter on Athena (lower). The blue vertical dotted lines mark the orbital separations corresponding to oscillation periods around the barycenter of $10^{5.6}$, $10^7$ and $10^{9}$, respectively, for a binary of mass $10^8M_\odot$. For comparison, XMM-Newton EPIC has $\delta E/E \sim 0.025$, making it insensitive to most MBH binary parameter space.

![Figure 1. The peak fractional change in energy $\delta E/E$ from eqn. 2 as a function of mass ratio $q$ and binary separation $a_b$. Horizontal dashed red lines denote the planned energy resolution at 6.40keV for Astro-H ($\sim 6eV$) and Athena($2eV$). The blue vertical dotted lines mark the orbital separations correspond to oscillation periods around the barycenter of $10^5$, $10^7$, and $10^9$ s respectively, for a binary of mass $10^8M_\odot$. For comparison, XMM-Newton EPIC has $\delta E/E \sim 0.025$, making it insensitive to most MBH binary parameter space.](image)

where $\omega(0)$ is the initial angle value, $\varpi_{\text{disk}}$ is the rate of (retrograde) precession of periaurus due to the interaction between the secondary and the disk (analagous to the gravitational tugs between planets in the planetary case), $\varpi_{\text{LK}}$ is the rate of precession of periaurus due to the interchange of (e,i) due to the Lidov-Kozai (LK) mechanism, $\varpi_{\text{GR}}$ is the (geodetic) rate of precession of periaurus due to a Schwarzschild spacetime, $\varpi_{\text{LT}}$ is the precession rate of periaurus due to Lense-Thirring (LT) frame-dragging by a spinning primary and $\varpi_Q$ is the rate of precession of periaurus due to the quadrupole moment of the non-spherical (spinning) primary. Note that LT frame-dragging effects can lead to inner disk warping (Bardeen & Petterson 1977), so the angle of the inner disk to the observers sightline can be independent of the angle of orbital plane of the secondary (i in Fig. 2).

In planetary studies of the effect of planetary tugs on the radial velocity component of stars, $\nu$ tends to evolve slowly with time and the effect of co-orbital planets (equivalent to our $\varpi_{\text{disk}}$ term above), dominates over other terms. However, in the case of a merging MBH binary, GR effects

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1 Where the spin of the primary is important, $\Delta\varpi$ can be defined in terms of the precession of the orbital angular momentum of the secondary around the spin axis of the primary ($\Delta\Omega$) at fixed inclination and the precession of the periapsis within the orbital plane ($\Delta\omega$), as $\Delta\varpi = \Delta\omega + \cos(i)\Delta\Omega$ (Merritt 2013).
become important and we can approximate the precession of periapse of the secondary MBH orbit per 2π revolution as (Merritt 2012)

\[ \delta \omega \approx 6\pi F \left[ 1 \pm \frac{4s^2}{3} F^{1/2} \cos(i) + \frac{s^2}{4} F(1 - 4\cos^2(i)) \right] + \delta \omega_{\text{disk}}(4) \]

where the term in square brackets is \([\delta \omega_{\text{GR}} + \delta \omega_{\text{LT}} + \delta \omega_{\text{Q}}]\), \(F = r_g/(a_b c^2)\), \(s = \pm[0, 1]\) is the dimensionless spin parameter of the primary MBH and \(\delta \omega_{\text{disk}} = 2\pi q_{a_b} \ell/(1 + \ell)\), where \(q_{a_b} = M_r/(r_1 M_1)\) is the mass ratio of distributed (disk) mass at \(r < a_b\) to mass \(M_1\). The \(\delta \omega_{\text{GR}} = 6\pi F\) term dominates \(\delta \omega_{\text{disk}}\) when \(\ell^2 \leq (3r_g/a_b q_{a_b})^{2/3}\), which holds if \(a_b/r_g < M_1/(r_1 M_1)\) for modest \(e\), or broadly if \(a_b \leq 10^{-1-2} r_g\) for most realistic disk models. The contribution of spin terms \((\delta \omega_{\text{spin}} = \delta \omega_{\text{LT}} + \delta \omega_{\text{Q}})\) to the precession rate is small at wide binary separations, growing from \(\delta \omega_{\text{spin}}/\delta \omega_{\text{GR}} \sim 0.02\) at \(10^7 r_g\) to \(\delta \omega_{\text{spin}}/\delta \omega_{\text{GR}} \sim 0.2\) at \(10 r_g\). We ignore the effect of the LK mechanism (\(\delta \omega_{\text{LK}}\)) since it requires a tertiary (disk or satellite) at high relative inclination and more massive than the secondary (Ford, Kozinsky & Rasio 2000). However, since stalled SMBH are expected to occur on \(\sim\)pc scales in galactic nuclei (Milosavljević & Merritt 2001), it is possible that the LK mechanism could yield binary eccentricities \(e > 0\) in randomly observed MBH binaries even at very small \(\sim 100 r_g\) separation.

Fig. 2 shows \(\delta E/E\) for the centroid energy of the broad FeKα line as a function of a 2π orbit over two periods of oscillation of the primary about the binary barycenter. Solid lines depict MBH binaries (with \(e = 0.01, 0.1\)) at \(a_b = 100 r_g\) and the black dashed line depicts an MBH binary at \(a_b = 200 r_g\). A \(q = 0.01\) binary at \(a_b = 100 r_g\) yields an oscillation that is not detectable with Astro-H (dashed red lines) but is detectable with Athena \((\delta E/E \sim 3 \times 10^{-4})\). Even over only two periods of oscillation, the effects of GR precession on different binary configurations are starting to appear in the slight phase shift between the \(e = 0.01, 0.1\) curves and between the \(a_b = 100, 200 r_g\) curves in Fig. 2.

Fig. 3 shows an expanded version of Fig. 2, showing \(\delta E/E\) for the centroid energy of the broad FeKα line as a function of 2π orbit, over 40 orbits of the primary about the binary barycenter. The two periods of oscillation from Fig. 2 for \(q = 0.1\) are shown in Fig. 3 as a part of a three period oscillation between \(0.008\). The envelope for these oscillations assuming \(e = 0.01, 0.1\) is extended to 40 orbits, revealing the modulating effects of GR-dominated orbital precession of the secondary, showing up in oscillations of the primary around the barycenter. Also shown in Fig. 3 are the envelope of oscillations of the barycenter of a \(q = 0.01\) binary with \(a_b = 100 r_g\) lasting for 40−23 which will therefore not be detectable with Astro-H (red dashed lines), but will be detectable with Athena (assuming \(\delta E/E \sim 3 \times 10^{-4}\)). Fig. 3 also shows the limiting case of the envelope of oscillations due to a \(q = 1\) MBH binary at \(a_b = 500 r_g\) with \(e = 0.1, 0.01\) (assuming only one MBH has an associated broad FeKα line for simplicity). Note that a 1.2Ms exposure corresponds to 40 orbits at 100 r_g around a \(M_b = M_1/10^8 M_\odot\) SMBH (see observing strategies below).
2.2 The broad and narrow FeKα line components

Broad FeKα lines are observed in several nearby active galactic nuclei (AGN) (e.g. Nandra et al. 1997; Bracco et al. 2007) and originate in fluorescent Fe deep in the gravitational potential well of the central supermassive black hole (see e.g. Reynolds & Nowak 2002, for a review). See McKernan et al. (2013) (and references therein) for a discussion of how the broad FeKα line component can be used to probe configurations of gas in the inner accretion disk and therefore test for possible MBH binaries. The narrow core of the FeKα line observed in AGN (e.g. Yaqoob & Padmanabhan 2004) originates in fluorescent cold gas (Fe i-Fe xvii) far from the supermassive black hole (Shu, Yaqoob & Wang 2010). We expect variations of the narrow core of the FeKα line to be uncorrelated on observing timescales with variations in the broad component and, more importantly, the narrow line centroid should not vary. Therefore, without knowing the absolute value of δE/E in the broad line in a given AGN, we can monitor its variation over time, by comparing the centroid of the narrow line with the oscillating centroid of the broad component.

Fig. 4 shows a 100ks simulated observation with the planned micro-calorimeter on Athena of an AGN at z = 0.01 with a 2-10keV photon flux of 4.5 × 10^{-12} erg cm^{-2} s^{-1}. The simulated data shown (binned at ~ 12eV) correspond to a 100ks exposure with δE/E equal to the average from the first positive oscillation for q = 0.1, a_b = 100r_g in Fig. 2 (or δE/E = 4 × 10^{-3}). The blue curve correpsonds to the best-fit model to these data and the red curve shows the best-fit model to an equivalent 100ks observation with δE/E = −0.004, equivalent to the average δE/E for orbits 5-10 in Fig. 2. The displacement between the two model fits by eye highlights how the oscillation of binaries around their barycenter will be easily detectable with Athena. The narrow FeKα line component (ignored in this model) should maintain the same centroid energy, allowing the relative shift in δE/E to be determined. The XSPEC toy model for the data in Fig. 4 was ZPHAABS(ZPOWERW+DISKLINE) where the absorbing Hydrogen column was 10^{23} cm^{-2} and the power-law index was −1.8. The primary diskline for the simulated data had an inclination angle of 60° and emissivity index k = −2.5, as well as a line normalization of 0.1 with respect to the continuum to illustrate the effect of the radial-velocity shift.

3 OBSERVING STRATEGIES

From Fig. 2 a 2π barycenter oscillation period for a q = 0.1, a_b = 100r_g binary will take ~ 1 year around a M_b = 10^6 M_☉ primary SMBH, but only ~ 8 hours around a M_b = 10^8 M_☉ primary SMBH. Since typical exposures of hundreds of ks (few days) are required to build up line fluxes with modern X-ray telescopes, techniques to search for MBH binaries in FeKα lines from AGN must depend on the moderately accurate estimates of the central mass (e.g. Gültekin et al. 2009; McKernan et al. 2010; Kormendy & Ho 2013). Large mass (~ 10^9 M_☉) SMBH are the simplest to test for barycenter oscillations, since a MBH binary will yield a monotonic change in the FeKα centroid energy between exposures over year (a_b ~ 100r_g) to multi-year (a_b ~ 10^4r_g) timescales. Moderate mass (~ 10^7 − 10^8 M_☉) SMBH will yield an oscillation over a single long exposure— a 300M_T a 10ks exposure corresponds to one orbit at a_b = 100r_g around a M_T = M_b/10^7 M_☉ SMBH. In these cases, a division of the exposures into two or three segments, at different phases, is sufficient to test for MBH binaries at moderate separations. The smallest mass (~ 10^6 M_☉) SMBH will be the most difficult to test for MBH binaries, since a several hundred ks exposure might contain tens of oscillations. The oscillations will broaden the wings of the broad FeKα component and models measuring the spin of a single SMBH (e.g. Brenneman et al. 2011) will therefore over-estimate of the spin of the SMBH. To test for tight MBH binaries in low mass AGN, and constrain q, a_b parameter space, long exposures must be chopped into periodic odd-even sets on short timescales at different phases, that may be co-added to test for radial velocity oscillations and modulation by precession effects. Note that the effective area of Athena (which falls off at higher energies) may be well exploited by AGN at modest redshifts.

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2 http://heasarc.gsfc.nasa.gov/cgi-bin/webspec

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Figure 4. A simulated 100ks observation with the Athena micro-calorimeter of an AGN at z = 0.01, with a 2-10keV flux of 4.5 × 10^{-12} erg cm^{-2} s^{-1}, which is generated by a diskline model (Fabian et al. 1989) (see text for details). Black data points correspond to simulated data where the average line centroid shift is δE/E = +0.004, which is the average of the first positive oscillation in Fig. 2 and the blue solid line corresponds to the best-fit model to these data. The red solid line corresponds to the best model fit when δE/E = −0.004, or the average δE/E for the first negative oscillation in Fig. 2 (simulated data not shown for clarity). The 200ks oscillation period corresponds to a q = 0.1 binary at a_b = 100r_g with M_1 = 6 × 10^6 M_☉.
CONCLUSIONS

Analagous to the search for planets around stars using radial velocity shifts in stellar spectral lines, radial velocity shifts will be imprinted on the broad FeKα line due to oscillations of a massive black hole binary (MBHB) around their barycenter. Near future X-ray telescopes (Astro-H or Athena) will have the energy resolution to search for such oscillations in the broad FeKα line observed in active galactic nuclei. We demonstrate that oscillations of MBHB about their barycenter with mass ratios $\gtrsim 0.01$, moderate binary separations ($a_\bullet \lesssim 1000r_g$) and moderate eccentricities ($e \sim 0.01 - 0.1$) will be detectable in multiple exposures of the broad FeKα line over timescales appropriate for the MBH mass. The periodic red- or blue-shift of the broad line energy centroid can be calibrated against the centroid of the narrow FeKα line.

The magnitude of precession of the secondary MBH orbit is dominated by GR effects and we demonstrate that this will be detectable for modest mass ratios and separations. Following Bayesian searches for radial velocity effects in stars due to tugs by unobserved planets (e.g. Brewer & Donovan 2013), we can take a similar approach to finding periodic signal in integrated (and multi-epoch) exposures of broad FeKα lines in AGN. Observations of such oscillations will reveal the closest MBH binaries and brightest gravitational wave sources in the local Universe.

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