Electromagnetic Emission from Compact Supermassive Black Hole Binaries

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Abstract

In this contribution, we discuss possible characteristics of electromagnetic (EM) emission from supermassive black hole binaries (SMBHBs). In particular, any detectable EM emission is likely to be time-variable, and contain unique spectral signatures, which should aid identifying SMHB binaries. Recent hydrodynamical simulations suggest quasiperiodic modulations in the accretion rate onto the BHs prior to coalescence. These time-variable EM signatures may be used to identify unique counterparts of gravitational wave sources expected to be detected by (e)LISA and by Pulsar Timing Arrays, and to discover binary SMBHs in time-domain EM surveys. As an example of the latter, the quasar PG1302-102 was recently discovered to have an apparent 5-yr periodic optical variability. We comment on the interpretation of this quasar as a SMBH binary candidate and its implications.

1 Introduction

Supermassive black holes (SMBHs) with masses in the range of $\approx 10^6 - 10^9 \mathrm{M}_\odot$ are present in the nuclei of most, and perhaps all, nearby galaxies [20]. In hierarchical structure formation models, galaxies are built up by frequent mergers between lower–mass progenitors. Each merger event is expected to deliver the nuclear SMBHs (e.g. [31, 25]), along with a significant amount of gas (e.g. [3]), to the central regions of the new post–merger galaxy. The inevitable conclusion is that SMBH binaries should form frequently in galactic nuclei over cosmic time–scales, and that this should often take place in gas–rich environments.

There is some empirical evidence for nuclear SMBHBs expected from the above. A handful of active SMBH pairs have been directly resolved, but only at relatively large projected separations of ~ 7 pc in the radio [26] and 0.1-1 kpc in the optical [32] and X-rays [10, 18]. A handful of more compact, unresolved SMBHB candidates have been identified through a variety of indirect techniques involving active galactic nuclei (AGN). The presence of binaries have been inferred from quasi-periodicities in light-curves, spectral features such as double-peaks or offsets of emission lines, or spatial structures of optical emission lines, and of radio jets and lobes (see, e.g., [19] for a review).

A particularly compelling recent case is the quasar PG1302-102, which has been interpreted as a binary with a $\sim$ 4yr rest-frame period [15]. Several dozen additional quasars have been recently discovered with apparent optical periodicities [21, 14], and it is natural to ask whether these can be interpreted as evidence for a population of merging SMBH binaries.

2 Expected Light-Curves and Spectra of SMBH Binaries

Over the past two decades, hydrodynamical simulations have converged on the behavior of gas near a SMBHB. In particular, if the gas near the binary resides in a thin accretion disk, then the torques from the binary create a central cavity, nearly devoid of gas, within a region about twice the orbital

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separation [1]. If the central cavity were indeed empty, no gas would reach the SMBHBs, and bright emission could not be produced. However, numerical simulations have consistently found residual gas inflow into the cavity [2, 22, 17, 16, 5, 27, 30, 24, 8, 11, 29], which accrete onto the individual BHs, and should produce detectable EM emission. As emphasized by several of these studies [8, 11, 29], the total accretion rate onto the binary is comparable overall to that onto a single SMBH with the same mass – in other words, the binary "propeller" is efficient in torquing and expelling gas from the central regions of the disk, but it is inefficient in suppressing the net accretion, occuring through narrow streams.

For near-equal mass binaries, efficient accretion persists even in the last stages of the merger, when the orbit decays rapidly as a result of the emission of gravitational waves – despite the fact that the orbital decay outpaces the viscous inflow time in the disk [12]. Early studies suggested that the gas missing from the inner cavity translates into a spectrum that is missing the corresponding high-energy emission (e.g. [23]). However, simulations have shown that the individual SMBHs can be fed through circumprimary and circumsecondary "minidisks", filling in this hard emission. In principle, a 'notch' could remain in the spectrum [28], after the thermal emission from the circumprimary, circumsecondary, and circumbinary disks are summed. However, the additional emission from the shocked accretion streams tends to fill in these notches [13]. See Figure 1.

As Figure 1 shows, the emission arising from the minidisks and the accretion streams is strongly enhanced compared to a single SMBH, and is also time-dependent. As shown by [7], as long as the mass ratio $q \equiv M_2/M_1$ exceeds the critical value of $q \gtrsim 0.05$, the accretion becomes strongly time-dependent, whereas for more unequal systems, with $q \lesssim 0.05$, the accretion is stable and steady. D'Orazio et al. 2015 [7] have identifed the loss of stable orbits in the horse-shoe region around the secondary's orbit, when $q \gtrsim 0.05$, as the physical origin of this transition.

The resulting periodicity pattern have also been found to strongly depend on the mass ratio. For $q \lesssim 0.05$, the disk is steady and the BH accretion rate displays no strong variability. For $0.05 \lesssim q \lesssim 0.3$, the accretion rate varies periodically on the timescale of the binary's orbit $t_{\rm bin}$, with additional periodicity at $\approx 0.5t_{\rm bin}$. Binaries with $0.3 \lesssim q \lesssim 0.8$ clear a lopsided central cavity in the disk, causing variability on three timescales. The dominant period, $(3-8)t_{\rm bin}$ is that of an over-dense lump, orbiting at the ridge of the cavity, with additional periodicities at $t_{\rm bin}$ and $\approx 0.5t_{\rm bin}$. The dominant period depends on the size of the cavity, and thus on disk parameters, such as temperature and viscosity. Finally, equal-mass ($q = 1$) binaries display variability at the longer lump period and at $\approx 0.5t_{\rm bin}$.

3 Applications to the Periodic Binary Candidate PG 1302-102

Graham et al. 2015 [15] have recently detected a 5.2 year periodic optical variability of the quasar PG 1302-102 at redshift $z = 0.3$, which they interpret as the redshifted orbital period $(1 + z)t_{\rm bin}$ of a supermassive black hole binary (SMBHB). We used our simulations to interpret this candidate.

This source has a rest-frame optical periodicity of $\approx$ 4yrs. However, if PG1302-102 is a near-equal mass binary ($q \gtrsim 0.3$), then, as explained above, the true binary period is a factor of 3-8 times shorter, close to $\approx$ 1 yr. This reduction would have several important implications [6]. First, the binary would be more compact, and would be in the GW-dominated inspiral regime. This would prove that SMBHBs can be bright even in this late stage of the merger, consistent with expectations from recent simulations of these late stages [12]. Second, the expected fraction of binaries with the shorter periods, among bright quasars, would be reduced by nearly two orders of magnitude. Quasars with such periodicities are rare (with 111 identified among 250,000 quasars; [14]), they would still be consistent with near-equal mass binaries, as long as most quasars are triggered by mergers. Third, shorter periods would imply higher binary speeds, and stronger relativistic effects. Finally, secondary peaks, at the true binary period and half-period would be expected in the periodogram of PG1302-102's light-curve. Although we have intriguingly found such peaks, we showed that they can be explained by aliasing alone, due to the uneven sampling of the light-curve [4]. The present data, however, already place upper limits on true secondary peaks, and our study demonstrates that with better data, the periodogram structure will be a useful diagnostic of binaries.

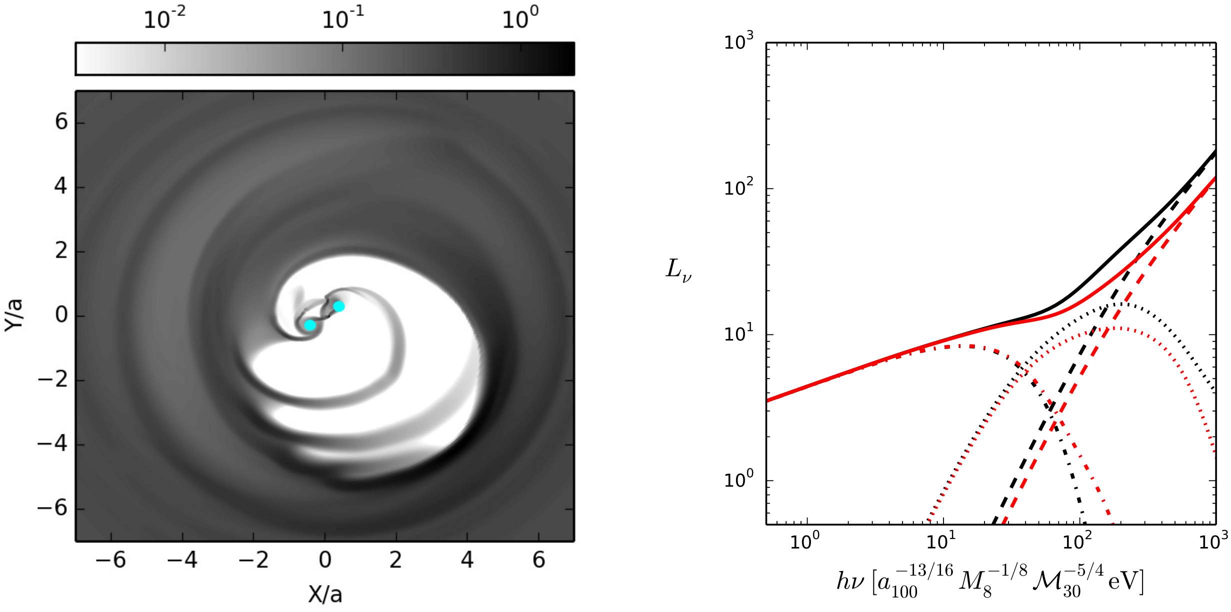

Figure 1: **Left panel**: *Snapshot of surface density* Σ *in a circumbinary disk, during quasi-steady state reached after* $\approx$ *3000 binary orbits (roughly a viscous time) in a 2D simulation. The surface density is normalized by its initial maximum value, and shown on a logarithmic scale in the inner region* $\pm 6a$ *(where* a *is the radius of the binary's circular orbit). Orbital motion is in the counter-clockwise direction.* **Right panel**: *Thermal spectra computed from the simulations shown in the left panel. The red curves are calculated three binaries orbits later than the black curves. The full spectra is represented by solid lines, the component arising only from minidisk regions within distance* $d < 0.5a$ *of either BH is represented by dashed lines, the "cavity" emission is represented by dotted lines, and the emission from the "outer region" is represented by dashed-dotted lines. Adapted from [13].*

A competing intepretation of PG1302-102 was offered in D'Orazio et al. 2015 [9], as an unequal-mass SMBHB with $q \sim 0.05$. In this case, the accretion rates onto the BHs may be steady, but the observed $\pm 15\%$ variability in the optical can be fully explained by the *inevitable* relativistic Doppler boosting of emission from the lower-mass secondary SMBH. As shown in Farris et al. 2014 [11], for this mass ratio, the secondary BH captures most of the accetion (out-accreting the primary by a factor of ~ 20). The relativistic Doppler boost from this fast-moving secondary (with orbital speed $v_2 \sim 0.06c$), by itself, can account for PG1302-102's variability, as long as the binary is massive ($\gtrsim 10^9$ $M_\odot$) and is viewed within $\sim 30^\circ$ of edge-on. The remarkably sinusoidal shape of PG1302's variability is further evidence for this scenario, as accretion variability tends to produce a more 'bursty' light-curve (Fig. 2).

The Doppler boost model further predicts that brightness variations in the ultraviolet light curve track those in the optical, but with a 2-3 times larger amplitude (see Figure 2). This prediction is relatively insensitive to the details of the emission process, and is consistent with available archival UV data. Follow-up UV and optical observations in the next few years can test this prediction, confirm the existence of a binary black hole in the relativistic regime, and clarify the origin of the periodic variability.

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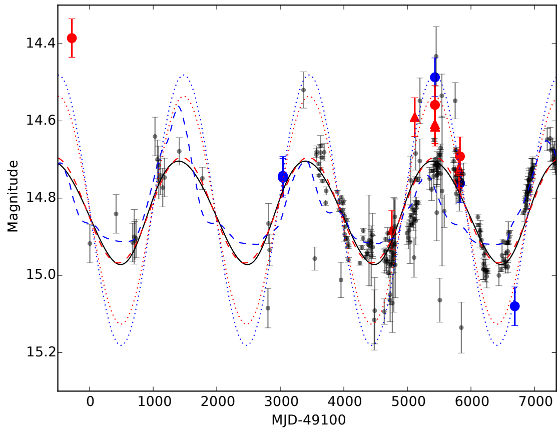

Figure 2: **The optical and UV light-curve of PG 1302-102.** *Black points with* 1σ *error bars show the optical data [15], superimposed with a best-fitting sinusoid (red dashed curve). The solid black curve shows the best–fit light–curve in the relativistic boost model. The blue dashed curve shows the best-fit model obtained by scaling the accretion rates found in a hydrodynamical simulation of an unequal-mass (*$q = 0.1$*) binary [8]. The additional circular data points with* 1σ *errors show archival near-UV (red) and far-UV (blue) spectral observations; the red triangles show archival photometric near-UV data-points. The UV data include an arbitrary overall normalization to match the mean optical brightness. The dotted red and blue curves show the best-fit relativistic optical light-curve with amplitude scaled up by factors of 2.17 and 2.57, expected based on the spectral slopes in the NUV and FUV bands, respectively. Adapted from [9].*

References

[1] P. Artymowicz and S. H. Lubow. Dynamics of binary-disk interaction. 1: Resonances and disk gap sizes. *ApJ*, 421:651–667, February 1994.

[2] P. Artymowicz and S. H. Lubow. Mass Flow through Gaps in Circumbinary Disks. *ApJL*, 467:L77+, August 1996.

[3] J. E. Barnes and L. Hernquist. Dynamics of interacting galaxies. *ARA&A*, 30:705–742, 1992.

[4] M. Charisi, I. Bartos, Z. Haiman, A. M. Price-Whelan, and S. Márka. Multiple periods in the variability of the supermassive black hole binary candidate quasar PG1302-102? *MNRAS, in press; e-print arXiv:1502.03113*, February 2015.

[5] J. Cuadra, P. J. Armitage, R. D. Alexander, and M. C. Begelman. Massive black hole binary mergers within subparsec scale gas discs. *MNRAS*, 393:1423–1432, March 2009.

[6] D. J. D'Orazio, Z. Haiman, P. Duffell, B. D. Farris, and A. I. MacFadyen. A reduced orbital period for the supermassive black hole binary candidate in the quasar PG 1302-102? *MNRAS*, 452:2540–2545, September 2015.

[7] D. J. D'Orazio, Z. Haiman, P. Duffell, A. I. MacFadyen, and B. D. Farris. A transition in circumbinary accretion discs at a binary mass ratio of 1:25. *MNRAS, submitted, e-print arXiv:1512.05788*, December 2015.

[8] D. J. D'Orazio, Z. Haiman, and A. MacFadyen. Accretion into the central cavity of a circumbinary disc. *MNRAS*, 436:2997–3020, December 2013.

[9] D. J. D'Orazio, Z. Haiman, and D. Schiminovich. Relativistic boost as the cause of periodicity in a massive black-hole binary candidate. *Nature*, 525:351–353, September 2015.

[10] G. Fabbiano, J. Wang, M. Elvis, and G. Risaliti. A close nuclear black-hole pair in the spiral galaxy NGC3393. *Nature*, 477:431–434, September 2011.

[11] B. D. Farris, P. Duffell, A. I. MacFadyen, and Z. Haiman. Binary Black Hole Accretion from a Circumbinary Disk: Gas Dynamics inside the Central Cavity. *ApJ*, 783:134, March 2014.

[12] B. D. Farris, P. Duffell, A. I. MacFadyen, and Z. Haiman. Binary black hole accretion during inspiral and merger. *MNRAS*, 447:L80–L84, February 2015.

[13] B. D. Farris, P. Duffell, A. I. MacFadyen, and Z. Haiman. Characteristic signatures in the thermal emission from accreting binary black holes. *MNRAS*, 446:L36–L40, January 2015.

[14] M. J. Graham, S. G. Djorgovski, D. Stern, A. J. Drake, A. A. Mahabal, C. Donalek, E. Glikman, S. Larson, and E. Christensen. A systematic search for close supermassive black hole binaries in the Catalina Real-time Transient Survey. *MNRAS*, 453:1562–1576, October 2015.

[15] M. J. Graham, S. G. Djorgovski, D. Stern, E. Glikman, A. J. Drake, A. A. Mahabal, C. Donalek, S. Larson, and E. Christensen. A possible close supermassive black-hole binary in a quasar with optical periodicity. *Nature*, 518:74–76, February 2015.

[16] K. Hayasaki, S. Mineshige, and L. C. Ho. A Supermassive Binary Black Hole with Triple Disks. *ApJ*, 682:1134–1140, August 2008.

[17] K. Hayasaki, S. Mineshige, and H. Sudou. Binary Black Hole Accretion Flows in Merged Galactic Nuclei. *PASJ*, 59:427–441, April 2007.

[18] S. Komossa, V. Burwitz, G. Hasinger, P. Predehl, J. S. Kaastra, and Y. Ikebe. Discovery of a Binary Active Galactic Nucleus in the Ultraluminous Infrared Galaxy NGC 6240 Using Chandra. *ApJL*, 582:L15–L19, January 2003.

[19] S. Komossa and J. A. Zensus. Compact object mergers: Observations of supermassive binary black holes and stellar tidal disruption events. *Review article in "Star clusters and black holes in galaxies across cosmic time", IAU Symposium No. 312, eds. R. Spurzem et al.; e-print arXiv:1502.05720*, February 2015.

[20] J. Kormendy and L. C. Ho. Coevolution (Or Not) of Supermassive Black Holes and Host Galaxies. *ARA&A*, 51:511–653, August 2013.

[21] T. Liu, S. Gezari, S. Heinis, E. A. Magnier, W. S. Burgett, K. Chambers, H. Flewelling, M. Huber, K. W. Hodapp, N. Kaiser, R.-P. Kudritzki, J. L. Tonry, R. J. Wainscoat, and C. Waters. A Periodically Varying Luminous Quasar at z = 2 from the Pan-STARRS1 Medium Deep Survey: A Candidate Supermassive Black Hole Binary in the Gravitational Wave-driven Regime. *ApJL*, 803:L16, April 2015.

[22] A. I. MacFadyen and M. Milosavljević. An Eccentric Circumbinary Accretion Disk and the Detection of Binary Massive Black Holes. *ApJ*, 672:83–93, January 2008.

[23] M. Milosavljević and E. S. Phinney. The Afterglow of Massive Black Hole Coalescence. *ApJL*, 622:L93–L96, April 2005.

[24] S. C. Noble, B. C. Mundim, H. Nakano, J. H. Krolik, M. Campanelli, Y. Zlochower, and N. Yunes. Circumbinary Magnetohydrodynamic Accretion into Inspiraling Binary Black Holes. *ApJ*, 755:51, August 2012.

[25] B. Robertson, T. J. Cox, L. Hernquist, M. Franx, P. F. Hopkins, P. Martini, and V. Springel. The Fundamental Scaling Relations of Elliptical Galaxies. *ApJ*, 641:21–40, April 2006.

[26] C. Rodriguez, G. B. Taylor, R. T. Zavala, A. B. Peck, L. K. Pollack, and R. W. Romani. A Compact Supermassive Binary Black Hole System. *ApJ*, 646:49–60, July 2006.

[27] C. Roedig, M. Dotti, A. Sesana, J. Cuadra, and M. Colpi. Limiting eccentricity of subparsec massive black hole binaries surrounded by self-gravitating gas discs. *MNRAS*, 415:3033–3041, August 2011.

[28] C. Roedig, J. H. Krolik, and M. C. Miller. Observational Signatures of Binary Supermassive Black Holes. *ApJ*, 785:115, April 2014.

[29] J.-M. Shi and J. H. Krolik. Three-dimensional MHD Simulation of Circumbinary Accretion Disks. II. Net Accretion Rate. *ApJ*, 807:131, July 2015.

[30] J.-M. Shi, J. H. Krolik, S. H. Lubow, and J. F. Hawley. Three-dimensional Magnetohydrodynamic Simulations of Circumbinary Accretion Disks: Disk Structures and Angular Momentum Transport. *ApJ*, 749:118, April 2012.

[31] V. Springel, T. Di Matteo, and L. Hernquist. Black Holes in Galaxy Mergers: The Formation of Red Elliptical Galaxies. *ApJL*, 620:L79–L82, February 2005.

[32] J.-H. Woo, H. Cho, B. Husemann, S. Komossa, D. Park, and V. N. Bennert. A sub-kpc-scale binary active galactic nucleus with double narrow-line regions. *MNRAS*, 437:32–37, January 2014.