An Electromagnetic Signature of Galactic Black hole Binaries Which Enter Their Gravitational-Wave Induced Inspiral

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Mergers of gas-rich galaxies lead to black hole binaries which coalesce as a result of dynamical friction on the ambient gas. Once the binary tightens to $\lesssim 10^3$ Schwarzschild radii, its merger is driven by the emission of gravitational waves (GWs). We show that this transition occurs generically at orbital periods of $\sim$1–10 years and an orbital velocity v of a few thousand km s^{-1}, with a very weak dependence on the gas infall rate ($v \propto \dot{M}^{1/8}$). Therefore, as binaries enter their GW-dominated inspiral, they inevitably induce large periodic changes in the broad emission lines of any associated quasar(s). The probability of finding a binary in tighter configurations scales as v^{-8} owing to their much shorter lifetimes. Systematic monitoring of the broad emission lines of quasars on timescales of years to decades can set a lower limit on the expected rate of GW sources for LISA.

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Introduction. Recent advances in general relativistic simulations of the final coalescence phase of black hole (BH) binaries through gravitational wave (GW) emission [1], sparked new interest in related electromagnetic (EM) signals [2]. New observational searches were initiated for wide BH binaries in their pre-merger phase or single quasars which are displaced from their host galaxy spatially or spectroscopically due to GW recoil after the merger[3]. In addition to testing the recent numerical predictions, such searches can be used to calibrate the expected rate of GW sources for the proposed LISA mission[17], as well as to reduce the error box on the source localization after LISA is launched. The next generation of simulations will attempt to incorporate gas dynamics and radiative transfer in order to calculate the EM counterparts to GW sources[4]. If these EM signatures are sufficiently unusual relative to typical quasar variability, one could search for them well before LISA is launched. Since BH binaries spend more time at larger separations, wider binaries should be more abundant in quasar surveys. In this paper we study a generic EM signature of the widest quasar binaries whose dynamics is dominated by GW emission.

Binary Parameters and Statistics. We consider two black holes with masses M_1 and M_2 in a circular orbit of radius a about each other[18]. Their respective distances from the center of mass are $a_i = (\mu/M_i)a$ $(i = 1, 2)$, where $\mu = M_1M_2/M$ and $M = M_1 + M_2$. We define the parameter $\eta = 4\mu/M$, which equals unity if $M_1 = M_2$ and is smaller otherwise. The orbital period is given by,

$$P = 2\pi(GM/a^3)^{-1/2} = 1.73 \text{ yr } a_{16}^{3/2} M_8^{-1/2}, \tag{1}$$

where, $a_{16} \equiv (a/10^{16} \text{ cm})$ and $M_8 \equiv (M/10^8 M_\odot)$. The angular momentum of the binary can be expressed in terms of the absolute values of the velocities of its members v_1 and v_2 as $J = \Sigma_{i=1,2} M_i v_i a_i = \mu v a$, where the relative orbital speed is

$$v = v_1 + v_2 = (2\pi a/P) = 1.15 \times 10^4 \text{ km s}^{-1} M_8^{1/2} a_{16}^{-1/2}\,. \tag{2}$$

We focus our discussion on mergers of gas-rich galaxies since those are most likely to result in bright quasars which are easy to observe. Hydrodynamic simulations of such mergers indicate that the associated BH binaries inspiral as a result of dynamical friction on the ambient gas[5]. The rate of inspiral slows down as soon as the gas mass interior to the binary orbit is smaller than μ, because the enclosed gas mass is not sufficient for carrying away the entire orbital angular of the binary J. Subsequently, momentum conservation requires that fresh gas will steadily flow into the binary orbit in order for it to shrink. The binary tightens by expelling gas out of its orbit (the "blender" effect [6]) and by torquing the surrounding disk [7, 10]. Fresh gas re-enters the binary's immediate environment as a result of turbulent transport of angular momentum in the surrounding disk. Since the expelled gas carries a specific angular momentum of $\sim va$, the coalescence time of the binary is simply related to the mass infall rate of fresh gas into the binary orbit $\dot{M}$, which in a steady state would equal the mass accretion rate of the surrounding gas disk,

$$t_{\rm gas} \approx (J/\dot{M}va) = \mu/\dot{M} = 10^7 \text{ yr } \eta \dot{\mathcal{M}}^{-1}. \tag{3}$$

Given that the quasar activity is fueled by inflow of gas, we quantify the mass infall rate in Eddington units $\dot{\mathcal{M}} \equiv \dot{M}/\dot{M}_E$, corresponding to the accretion rate required to power the limiting Eddington luminosity with a radiative efficiency of 10%, $\dot{M}_E = 2.5 M_\odot \text{ yr}^{-1} M_8$. Since $t_{\rm gas}$ is limited by the rate at which fresh gas refills the binary orbit, the binary spends equal amounts of time per log a (for a steady $\dot{\mathcal{M}}$) until GWs start to dominate its loss of angular momentum.

The coalescence timescale due to GW emission is given by [8],

$$t_{\rm GW} = \frac{5}{256}\frac{c^5 a^4}{G^3 M^2 \mu} = 2.54\times 10^5 \text{ yr } \frac{a_{16}^4}{\eta M_8^3}. \quad (4)$$

By equating $t_{\rm GW} = t_{\rm gas}$ we can solve for the orbital speed, period, and separation, at which GWs take over,

$$v_{\rm GW} = 7.3\times 10^3 \text{ km s}^{-1}\ \eta^{1/4}(\dot{\mathcal{M}} M_8)^{1/8}\ ; \quad (5)$$

$$P_{\rm GW} = 6.84 \text{ yr } \eta^{3/4} M_8^{5/8}\dot{\mathcal{M}}^{-3/8}\ ; \quad (6)$$

$$a_{\rm GW} = 8.1\times 10^{-3} \text{ pc } \eta^{1/2} M_8^{3/4}\dot{\mathcal{M}}^{-1/4}. \quad (7)$$

Remarkably, the orbital speed at which GWs take over is very weakly dependent on the gas inflow rate, $v_{\rm GW}\propto \dot{M}^{1/8}$. It generically corresponds to an orbital separation of order $\sim 10^3$ Schwarzschild radii ($2GM/c^2$). In an equal-mass binary, each BH moves relative to the center-of-mass at a speed of $\frac{1}{2}v_{\rm GW}$. Coincidentally, this orbital speed happens to be similar to the velocity width of the broad emission lines (BEL) of quasars[9]. This fortunate coincidence implies that the time-dependent gravitational potential and UV illumination of the binary members will introduce variability into the spectroscopic shape of any associated BEL. Even if the BEL clouds are produced in the outer edge of the accretion disk around one of the BHs, they will be affected by the combined gravitational force and UV illumination from both BHs.

We therefore robustly predict that *when BH binaries from mergers of comparable-mass, gas-rich galaxies start to inspiral by GW emission, they would show variability with a period of years to decades (for $M\sim 10^6$–$10^9 M_\odot$) in any associated BEL, across a range of Doppler velocities comparable to the BEL spectral width.*

The periodic Doppler shift is expected to be smaller for unequal mass binaries. If each BH controls the spectroscopic centroid of its own BEL, the BEL associated with M_i will be shifted by $v_i = (M_j/M)v$, for $(i,j) = (1,2)$ or $(2,1)$. Of course, the different UV luminosities emitted by the BHs could modify this expectation. Double-peaked lines are expected only if both BH have an accretion disk.

The probability of observing periodic BEL shifts due to a binary transitioning to a GW-dominated inspiral, $\mathcal{P}_{\rm GW}$, depends on the unknown fraction of the associated quasar activity which overlaps with this final phase of binary coalescence. In case accretion is suppressed by the blender effect [6], it is possible that no BEL emission is observable during the GW-dominated inspiral phase. However, existing numerical simulations[7, 10] indicate that accretion should continue during this phase. If quasar emission persists throughout the coalescence process at a constant $\dot{\mathcal{M}}$ due to the abundant supply of ambient gas, then it is as likely to find binaries with separation $a_{\rm GW}\sim 10^{-2}$ pc as it is to find them at a separation of tens of pc, where the enclosed gas mass is comparable to μ. In that case, the prospects for discovering a quasar with a periodic BEL shift over a decade timescale are good, since an example for a tight binary at a projected separation of ~ 7.3 pc has already been identified[11] and two sub-pc candidates have been reported[12, 13].

The probability of finding a binary in configurations that are deeper in the GW-dominated regime diminishes rapidly at increasing orbital speeds, $\mathcal{P} = \mathcal{P}_{\rm GW}(v/v_{\rm GW})^{-8}$.

Discussion. Future monitoring of the broad emission lines of quasars on timescales of years to decades can set a lower limit on the expected rate of GW sources for LISA. Preliminary studies could make use of archival spectroscopic data from SDSS and motivate the implementation of narrow-band filters in photometric variability surveys such as the future LSST[19].

Previous searches for BEL variability reported no detections of periodicity in samples of thousands of quasars[14], although there are examples of long-term variability without a measured period [16].

Since quasar BEL are known to vary for other reasons[15], it is crucial to identify periodicity before classifying a candidate source as viable. In confirmed cases, measurements of the period and velocity shift can be used to solve for M and a, and the quasar luminosity could be used to estimate $\dot{M}$. One could then verify whether $t_{\rm gas}$ is indeed of order $t_{\rm GW}$ for reasonable values of η.

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