Supermassive black hole mergers as dual sources for electromagnetic flares in the jet emission and gravitational waves

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We present a new type of observation relating the gravitational wave emission of supermassive black hole mergers to their electromagnetic counterparts. This dual emission involves variability of a relativistic jet arising from the spin-orbit precession of the supermassive black hole binary at its base.

1 Introduction

The large number of parameters of the gravitational wave (GW) sources induces degeneracies obstructing their identification from GW observations alone. Coincident detections of electromagnetic (EM) and GW signatures from supermassive black hole (SMBH) coalescence would significantly improve this situation.

EM signatures from SMBH binaries could arise through interaction with the surrounding matter. An early attempt to estimate the EM counterparts of Advanced LIGO and Virgo GW sources (neutron star-neutron star or neutron star-black hole binary) by Sylvestre (2003) reviews three different mechanisms: magnetospheric interactions, radioactive decay of ejected material, and relativistic blast waves.

Some of the theoretical studies model the merging BH binary as immersed in a gas cloud or surrounded by a circumbinary disk (Armitage & Natarajan 2002, 2005; Cuadra et al. 2009; Dotti et al. 2007; Escala et al. 2005; Roedig et al. 2011). Other models involve interaction with a nuclear star cluster (Khan, Just, & Merritt 2011; Preto et al. 2011; Zier & Biermann 2001, 2002). The hardening of the binary by angular momentum and energy exchange with stars was also investigated (Berczik et al. 1996; Perets & Alexander 2008; Quinlan 1996; Sesana, Haardt & Madau 2007). Observational evidence is restricted for such disks, as direct observations of merging SMBH systems are very sparse; the best claim (Rodriguez et al. 2006) has been supported by Morganti, Emonts and Oosterloo (2009).

Krolik (2010) has shown that the duration of the EM signal is proportional to the mass of the gas near a pair of merging BHs, and rather longer than the merger event. Both the realignment of the gas orbit to the spin orientation of the newly formed BH and the orbital adjustment to the mass lost by GW augment the EM radiation over longer timescales.

Milosavljevic and Phinney (2005) have studied how the binary hollows out the surrounding gas and shrinks slowly compared to the viscous timescale of a circumbinary disk. The truncation of the inner gas disk at a radius where gravitational torque from the binary equals the viscous torque leads to a diminished accretion onto the black holes. The viscous evolution of the hollow disk will be visible in X-rays. According to a Newtonian calculation of the EM afterglow (Shapiro 2010) both the temporal increase in the total EM flux and the hardening of the spectrum will confirm the interpretation of a GW interferometer signal as arising from the merger of a binary BH.

Arguments supporting the occurrence of the afterglow much sooner after the merger than previously estimated have been presented by Tanaka and Menou (2010). The birth of a quasar as triggered by the merger of the SMBH host galaxies is then preceded by this afterglow, and it is proposed that all-sky soft X-ray surveys could identify them (Tanaka, Haiman & Menou 2010). Multiple EM flares from tidally disrupted stars could also follow the SMBH binary merger (Stone & Loeb 2011).

The extent to which SMBH mergers in quasars could be detected through GW emission has been discussed by Kocsis et al. (2006). The size and orientation of the three-
dimensional error ellipse in solid angle and redshift within which a LISA (Laser Interferometer Space Antenna) (Arun et al. 2009) event could be localized using the GW signatures was given. Assuming that BH mergers are accompanied by gas accretion leading to Eddington-limited quasar activity, the number of quasars in a typical LISA error volume gave at low redshifts a single near-Eddington quasar at $z=1$. For rapidly spinning SMBHs this result may be extended up to $z=3$. The possibility that a dedicated optical or X-ray survey could identify coalescing SMBH binaries statistically, as a population of periodically variable quasars has been discussed (Haiman, Kocsis & Menou 2009).

Dotti et al. (2006) have considered the mutually exclusive possibilities of detecting either an EM precursor, during the last year of a GW-driven inspiral, or an afterglow within a few years after coalescence. The precursors correspond to on-off states of accretion on to a primary SMBH heavier than $\sim 10^7 M_\odot$ (a bright X-ray source decaying), and they are associated with galaxies containing ongoing starbursts. Lighter binaries, by contrast, exhibit an off-on accretion flow rising in $< 20$ years, leading to an EM afterglow. The possible recoil of the merged SMBH could produce strong shocks, resulting in an afterglow with characteristic photon energy increasing in time from the UV to the soft X-ray range, between one month and a year after the merger (Lippai, Frei & Haiman 2008), provided the Schmittman and Buonanno (2007) empirical formula for the dependence of the kick velocity on spins and mass ratios is adopted. The possibility of detecting prompt EM counterparts was discussed by Kocsis, Haiman and Menou (2008), both for transient signals and by cross-correlating the period of any variable EM signal with the quasi-periodic gravitational waveform over 10–1000 cycles. The effect of EM counterparts to GWs from a binary BH system on plasmas and EM fields in their vicinity was also considered (Palenzuela, Lehner & Yoshida 2010). The binary’s dynamics induces time dependence in the form of a variability in electromagnetically induced emissions and an enhancement of EM fields in the final stages of the merger.

Using a general relativistic, hydrodynamical study of the late inspiral phase and merger of equal-mass, spinning SMBH binaries immersed in hot gas flows, Bode et al. (2010) have argued that variable EM signatures correlated with GW emission can arise due to shocks, accretion, relativistic beaming, and Doppler boosting modulated by the binary orbital motion. The effect is largest for binary systems with the individual BH spins aligned with the orbital angular momentum. The frequency of the EM oscillations and GWs was found to be equal and the variations in luminosity to be within a factor of 2. The most massive binaries detectable in the LISA band may be identified in EM searches out to within a factor of 2. The most massive binaries detectable in EM searches out to within a factor of 2.

A binary moving in a uniform magnetic field anchored to a circumbinary disk was considered by Mósta et al. (2010) for configurations where the spins were either aligned or anti-aligned with the orbital angular momentum. The emitted EM waves mimic the phase of the GWs but have quite small amplitudes and peak at frequencies unaccessible to radio astronomical observations. In particular, the energy emission in EM waves was shown to be 13 orders of magnitude smaller than in GW and the corresponding luminosity is also much smaller than the accretion luminosity for systems accreting close to the Eddington rate. Nonetheless it was conjectured, that with a small and stable accretion rate of the circumbinary disk over the timescale of the final inspiral, the EM emission will alter the accretion rate through magnetic torques; hence it may be observable indirectly.

In another mechanism the GWs themselves induce EM waves propagating away through the ambient gas, and shear which is eventually dissipated as heat (Kocsis & Loeb 2008).

The symbiotic systems of black holes, accretion disks and magnetospheres however include another important element, not yet considered. This is the energetic jet a SMBH often emits in the direction of its spin. The SMBH spin and the jet spectrum correlate (Kun et al. in prep.). When a SMBH lying at the base of the jet is moved around by the inspiral of a smaller black hole, then a violent EM wave travels along the magnetic field structure of the jet and the geometry of the jet at its base is also distorted.

The purpose of this paper is to investigate in a simple model how the observations on the periodicity in a jet at the base of which there is a SMBH binary could result in complementary information for GW detection by the LISA space mission.

2 Flares in the jet spectrum due to spin-orbit precession

Most of the jets will have an orientation quite far from the line of sight; however, many jets pointing close to us are detected by radio techniques. This detection is enhanced by a strong selection effect: relativistic boosting of the emission from the jet is so powerful, that half of all radio sources detected at 5 GHz are relativistic jets pointed nearly at us (Chini et al. 1988; Eckart et al. 1986, 1987, 1989; Gregorini et al. 1984; Kühr et al. 1981a, 1981b).

If for some reason a jet shows a precessional evolution, and it is also relativistic, when it comes close to our line of sight, it will produce significant variability at all wavelengths, mostly detectable in the radio, hard X-ray and gamma-ray spectrum. Such a precession could originate from the spin-orbit interaction in a SMBH binary lying at the base of the jet. Due to this interaction the spins undergo a precessional motion about the orbital angular momentum $L$, each spin sweeping over a cone. Gergely and Biermann (2009) explored in detail the consequences of the simultaneous spin-orbit precession and GW backreaction. For the typical mass ratio range of 1:3 to 1:30 it was shown that the second spin can be neglected as $S_2/S_1 = \nu^\theta \chi_2/\chi_1$ (where $\chi_1,2 = cS_1,2/Gm_1^2$ are the dimensionless spin parameters, $G$ is the gravitational constant, $c$ the speed of light and $\nu = m_2/m_1 < 1$ the mass ratio). Thus the precession
of the dominant spin \( \mathbf{S}_1 \) can be regarded to occur about the total angular momentum \( \mathbf{J} = \mathbf{L} + \mathbf{S}_1 \). For this mass ratio range a reorientation of \( \mathbf{S}_1 \) occurs during the inspiral. In the process the cone swept by the jet will change its opening angle. As at the end of the inspiral the direction of the dominant spin becomes closely aligned to the total angular momentum, the opening of the cone becomes quite narrow. The spin-flip can be visualized as the narrowing in time of the precession cone until \( \mathbf{S}_1 \) becomes quasi-aligned to \( \mathbf{J} \). Therefore, any jet variability detected due to this mechanism will be a transient phenomenon.

The period \( T_p = 2\pi \Omega_p^{-1} \) of the precession (where \( \Omega_p \) is the precessional angular velocity) gives the precession timescale, approximated as (Gergely & Biermann 2009)

\[
\frac{1}{T_p} \approx \frac{c^3 \eta}{\pi G m} \varepsilon^{5/2} \frac{J}{L} = \frac{c^3 \eta}{\pi G m} \varepsilon^{5/2} \sqrt{1 + \left( \frac{S_1}{L} \right)^2},
\]

where \( m = m_1 + m_2 \) is the total mass, \( \eta = m_1 m_2 / m^2 = \nu / (1 + \nu)^2 \) the symmetric mass ratio, \( \varepsilon = G m / c^2 r \) the post-Newtonian (PN) parameter and \( r \) the orbital separation. For the last approximation \( S_1 \) and \( L \) were taken as perpendicular, in order to be able to further employ

\[
\frac{S_1}{L} = \varepsilon^{1/2} \nu^{-1} \chi_1,
\]

The typical time-scale of the inspiral is

\[
\frac{1}{T_{\text{insp}}} = \frac{\dot{L}}{L} = \frac{32 c^3 \eta \varepsilon^4}{5 G m},
\]

hence the ratio of these time-scales becomes

\[
\frac{T_{\text{insp}}}{T_p} = \frac{5}{32 \pi} \varepsilon^{-3/2} \sqrt{1 + \left( \frac{\varepsilon^{1/2} \nu^{-1} \chi_1}{2} \right)^2}.
\]

This ratio is smallest in the last stages of the inspiral, represented on Fig. 1, indicating that the time-scale under which GWs cause significant changes in the orbit is typically two orders of magnitude larger than the precession time-scale. In this stage an observed variability in the jet of the order of a day, if due to rapid precession would imply few remaining months for the evolution of the binary until the merger and related GW emission.

### 3 Orbital characteristics of the binary from observations

For simplicity we assume that the dominant SMBH is maximally spinning (\( \chi_1 = 1 \)). Let the angles between \( \mathbf{S}_1 \) and \( \mathbf{J} \) be \( \beta \), while between \( \mathbf{S}_1 \) and \( \mathbf{L} \) be \( \kappa \) (which, to leading order GW radiation stays constant, Gergely, Perjés & Vasuth 1998). Additionally, the law of sines and Eq. (2) allow us to express \( \kappa \) as

\[
\kappa = \beta + \arcsin \left( \varepsilon^{1/2} \nu^{-1} \sin \beta \right).
\]

We identify the period of the flares in the jet with the \( T_p \). A more accurate estimate combines the next-to-the-last expression (1) and the law of sines as

\[
T_p (\varepsilon, \nu, \kappa, \beta) = \frac{\pi G m (1 + \nu)^2 \sin \beta}{c^2 \varepsilon^{5/2} \nu \sin \kappa}.
\]

As the frequency of the gravitational wave to leading order is

\[
f_{GW} = \frac{c^3}{\pi G m} \varepsilon^{3/2},
\]

the jet variability period can also be expressed as

\[
T_p (\varepsilon, \nu, f_{GW}, \beta) = \frac{1 + \nu}{\varepsilon \nu} \frac{2 \sin \beta}{\sin \kappa} f_{GW}^{-1}.
\]

The GW frequency \( f_{GW} \) and PN parameter \( \varepsilon \) determine the time \( T_{\Delta \beta} \) characterizing how long the jet variability is observed. Gergely and Biermann (2009) have derived the evolution of \( \kappa - \beta \) under radiation reaction (their Eq. (36)). Employing the sin theorem we find

\[
\dot{\beta} \approx \frac{32 c^3 \varepsilon^{9/2} \sin^2 \beta}{5 G m (1 + \nu)^2 \sin \kappa}.
\]

We approximate with \( \Delta \beta = - \int_{T_{\Delta \beta}}^{\infty} \dot{\beta} dt \approx - \dot{\beta}_0 T_{\Delta \beta} \) the angle under which the variability in the jet spectrum is still detectable (the variability is observable in some range \( (\beta_0 - \Delta \beta / 2, \beta_0 + \Delta \beta / 2) \)). Hence \( T_{\Delta \beta} \) becomes entirely determined by the set \( \varepsilon, \nu, \kappa, \Delta \beta \) (or, by employing Eq. (7),

\[
\begin{array}{cccc}
\beta [\%] & \kappa [\%] & T_p [\text{days}] & T_{\Delta \beta} [\text{days}] \\
20 & 40 & 116 & 1041 \\
25 & 50 & 120 & 812 \\
30 & 60 & 126 & 656 \\
35 & 70 & 133 & 541 \\
40 & 80 & 142 & 451 \\
\end{array}
\]
by $\varepsilon, \nu, f_{GW}, \beta, \Delta \beta$):

$$T_{\Delta \beta} = \frac{5\Delta \beta}{32\pi} \frac{(1 + \nu)^2 \sin \kappa}{\varepsilon^3 \sin^2 \beta} f_{GW}^{-1}.$$ (10)

The ratio $T_{\Delta \beta}/T_p$ has a simpler parameter dependence

$$\frac{T_{\Delta \beta}}{T_p} (\varepsilon, \nu, \beta; \Delta \beta) = \frac{5\Delta \beta \nu \sin^2 \kappa}{32\pi \varepsilon^2 \sin^3 \beta}.$$ (11)

For a given mass ratio $\nu$, given inclination $\beta$ and a given observational sensitivity $\Delta \beta$ the set of observables $T_p$ and $T_{\Delta \beta}/T_p$ will determine the PN parameter $\varepsilon_{\Delta \beta}$ and the associated GW frequency $f_{GW}$ (or, equivalently, the total mass).

For illustration, in Table 1 we give $T_{\Delta \beta}$ and $T_p$ for $\nu = 0.1$, $\varepsilon_{\Delta \beta} = 0.01$ and $m = 10^6 M_{\odot}$ for various values of $\beta$, and $\Delta \beta = 1^\circ$.

4 Conclusion Remarks

SMBH encounters typically do not have equal masses, nor do they usually have extreme mass ratios, implying that a spin flip very likely happens during the inspiral. Such spin-flips provide a mechanism to form X-shaped RGs via a rapid reorientation of the jet direction (Gopal-Krishna et al. 2012; Mezcua et al. 2011, 2012). The spin-flip can be visualized as the narrowing in time of the precession cone until $S_1$ becomes quasi-aligned to $J$. A jet swerving into the line of sight would immediately constitute an extreme brightening of a flat spectrum radio source, and precession of such a source on scale of a few days would produce very strong flaring. All extremely variable AGN are flat spectrum radio sources near 5 GHz (Eckart et al. 1986; Gregorini et al. 1984). Therefore such a source would be immediately recognizable, and some of the most extreme flaring sources among the known flat spectrum radio sources are clear candidates to be very close to a merger.

Any jet variability detected due to this mechanism will be a transient phenomenon, as the cone continues to narrow. Assuming that such strong variability in the jets is detected as a transient phenomena, there will be two timescales given by the jet observations: the period of the variability (we identify this with the spin-orbit precessional period) and the time the transient phenomenon lasts, as well as an angle $\Delta \beta$ determined by the sensitivity of the observations. We have determined the dependence of these observables on the mass ratio $\nu$, PN parameter $\varepsilon$, jet inclination $\kappa$ vs. the orbital plane and GW frequency $f_{GW}$, at the time of observation. These additional jet observables greatly contribute to reduce the known degeneracies in the parameter space by pure GW detection.

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