Massive black hole binary plane reorientation in rotating stellar systems

Alessia Gualandris,1⋆ Massimo Dotti2 and Alberto Sesana3

1Max-Planck Institut für Astrophysik, Karl-Schwarzschild-Str. 1, D-85741 Garching, Germany
2Dipartimento di Fisica G. Occhialini, Università degli Studi di Milano Bicocca, Piazza della Scienza 3, 20126 Milano, Italy
3Albert Einstein Institut, Am Mühlenberg 1, Golm, D-14476, Germany

Accepted 2011 November 7. Received 2011 October 31; in original form 2011 September 3

ABSTRACT
We study the evolution of the orientation of the orbital plane of massive black hole binaries (BHBs) in rotating stellar systems in which the total angular momentum of the stellar cusp is misaligned with respect to that of the binary. We compare results from direct summation N-body simulations with predictions from a simple theoretical model. We find that the same encounters between cusp stars and the BHBs that are responsible for the hardening and eccentricity evolution of the binary lead to a reorientation of the binary orbital plane. In particular, binaries whose angular momentum is initially misaligned with respect to that of the stellar cusp tend to realign their orbital planes with the angular momentum of the cusp on a time-scale of a few hardening times. This is due to angular momentum exchange between stars and the BHBs during close encounters, and may have important implications for the relative orientation of host galaxies and radio jets.

Key words: black hole physics – methods: numerical – stars: kinematics and dynamics – galaxies: nuclei.

1 INTRODUCTION
In the standard ΛCDM cosmological scenario, massive black hole binaries (BHBs) are the natural outcome of mergers of massive galaxies (Begelman, Blandford & Rees 1980). The orbital decay of BHBs has been studied in detail under the assumption of purely stellar systems (e.g. Makino & Funato 2004; Berczik, Merritt & Spurzem 2005; Baumgardt, Gualandris & Portegies Zwart 2006; Merritt, Mikkola & Szell 2007; Sesana, Haardt & Madau 2007; Sesana 2010) as well as gaseous environments (e.g. Armitage & Natarajan 2002, 2005; Escala et al. 2004, 2005; Dotti, Colpi & Haardt 2006; Dotti et al. 2007, 2009; Cuadra et al. 2009; Lodato et al. 2009; Roedig et al. 2011).

Most studies of the evolution of BHBs in stellar environments consider non-rotating, spherically symmetric nuclei, despite the natural occurrence of rotation in merger remnants (e.g. Gualandris & Merritt 2011). Simulations of MBHs in spherical stellar systems predict a stalling of the binary evolution at parsec scale separations, the ‘final parsec problem’ (Milosavljević & Merritt 2003), which may or may not be avoided in the presence of gas dissipation. A BHB can, however, reach coalescence even in a completely gas-poor environment, if embedded in a non-spherically symmetric stellar distribution. Purely dissipationless simulations of non-spherical galaxy models (Berczik et al. 2006; Berentzen et al. 2009) or galaxy mergers (Gualandris & Merritt 2011; Khan, Just & Merritt 2011; Preto et al. 2011) find continuing hardening of the binary down to separations where energy loss due to emission of gravity waves becomes efficient. Simulations by Gualandris & Merritt (2011) show that efficient hardening is achieved even in systems close to axisymmetry. This departure from spherical symmetry is due to the rotation introduced by the merger, which results in an enhanced rate of stars interacting with the binary.

A comprehensive and systematic study of the evolution of BHBs in rotating stellar cusps is still missing. Sesana, Gualandris & Dotti (2011) (hereafter Paper I) studied the evolution of the eccentricity of unequal-mass BHBs in rotating systems by means of a hybrid analytical/three-body scattering formalism as well as full N-body simulations. They found a strong dependence of the eccentricity evolution of the binary on the degree of co-rotation in the stellar cusp, with binaries increasing their eccentricity in cusps containing a significant fraction of counter-rotating stars. This is relevant to the case of galactic minor mergers, in which counter-rotating systems can be produced as a result of rotation in the larger galaxy, thereby forming very eccentric binaries.

Another important and potentially observable parameter is the orientation of the binary orbital plane. Its evolution has been studied in spherical and isotropic systems (Merritt 2002; Gualandris & Merritt 2007). Due to the lack of any preferential direction in these systems, the orbital plane of the binary can only undergo a random walk, resulting in small changes in the orbital plane on long time-scales. Here we study the evolution of the orbital plane of BHBs in rotating stellar systems, where, as will be discussed, a significantly larger reorientation is expected.

This Letter is organized as follows. In Section 2, we describe the evolution of the binary orbital plane in spherically symmetric
models. In Section 3, we describe the case of rotating models, comparing results from N-body simulations with a simple analytical model. Final remarks are presented in Section 4.

2 NON-ROTATING CUSPS

The orientation of the orbital plane of BHBs embedded in non-rotating, isotropic stellar nuclei has been studied for the first time by Merritt (2002). In such systems, repeated encounters passing stars cause the orientation of the binary to undergo a random walk (a ‘rotational Brownian motion’, in Merritt 2002). From simple analytical arguments, the expected change in orientation on one hardening time $T_h = \lvert\dot{a}/\dot{a}\rvert$ of the binary (which is of the order of 50–60 initial binary orbital periods) is (Gualandris & Merritt 2007)

$$\Delta \theta \propto q^{-1/2} \left( \frac{m_*}{M_{\text{BHB}}} \right)^{1/2} (1 - e^2)^{-1/2},$$

where $q = M_2/M_1$ is the binary mass ratio, $M_{\text{BHB}}$ is the total mass and $e$ is the orbital eccentricity. Numerical scattering experiments have constrained the normalization in equation (1) only for circular binaries. Neither the dependence on the eccentricity nor on the mass ratio has been tested numerically. In the case of a binary with $M_{\text{BHB}} = 10^7 M_\odot$ and $q = 10^{-3}$, the expected reorientation is $\Delta \theta \approx 9^\circ$.

Here we check the validity of equation (1) by performing N-body simulations of binaries with different eccentricities (in the range of 0–0.99) embedded in non-rotating stellar cusps. We use the direct summation N-body code \textsc{grape} (Hafst et al. 2007) in combination with the Sapporo library (Gaburov, Hafst & Portegies Zwart 2009) to accelerate the computations on GPU hardware. In our integrations, we adopted $M_1 = 10^6 M_\odot$ and $q = 1/81$ and set the initial semimajor axis to $a_i = 0.06$ pc. The MBHs are embedded into a stellar cusp following a Bahcall–Wolf $\rho(r) \sim r^{-7/4}$ density profile at distances smaller than 1 pc, with total mass $M_c \sim 2.5 \times 10^5 M_\odot$ and a mass enclosed in the binary orbit equal to $2M_2$. The cusp is modelled with $N = 32k$ equal-mass particles, resulting in a black hole to star mass ratio of $m_* / M_{\text{BHB}} = 7.5 \times 10^{-6}$. Fig. 1 shows the degree of realignment of the binary plane as a function of the initial eccentricity. The dashed line indicates the dependence expected from the analytical model, while the points show the results of our N-body integrations. The agreement is remarkable.

For a given binary, the reorientation in a non-rotating system does not depend only on the mass density and velocity field of the stars but also on the mass ratio between the binary and a single star in the cusp.\footnote{Note that this ratio is properly defined only for a single-mass stellar cusp. In the presence of a mass spectrum, the mean mass of the interacting stars is a good proxy for $m_*$.}

A binary embedded in a stellar cusp of total mass $M_{\text{tot}}$ would, on average, experience a greater realignment as a result of few encounters with massive stars than as a result of many encounters with low-mass stars. This feature is typical of any random walk process, in which there is no preferential direction for the change of the binary plane in a single encounter and changes due to different encounters tend to cancel each other out. This is illustrated in the lower panel of Fig. 2, which shows the dependence of the change in $\theta$ on the number of particles used to model the cusp, i.e. on the $m_* / M_{\text{BHB}}$ mass ratio. The agreement between the numerical results (full circles) and equation (1) (solid line) is outstanding.

3 ROTATING CUSPS

Here we study, for the first time, the reorientation of a massive BHB embedded in a cusp with net rotation. To this aim, we perform high-accuracy N-body simulations similar to those presented in the previous section, the only difference being the degree of rotation that we enforce in the cusp. This is obtained, as in Paper I, by reversing the sign of all velocity components for a random subset of cusp stars, at the time when the BHB is added. In particular, we generated models with a fraction $\mathcal{F} = 0.875$ of co-rotating stars and varied the initial angle $\theta_0$ between the total angular momentum of the cusp and the angular momentum of the binary. We considered cases with $\theta_0 = 0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ$ and $150^\circ$.

The evolution of $\theta$ as a function of time is shown in Fig. 3 (solid lines) for all runs. Binaries whose angular momentum is initially misaligned with respect to that of the cusp tend to realign it on a time-scale of a few hardening times. The realignment can be quite significant, with an average change in $\theta$ of the order of 50 per cent...
The evolution of $\theta$ can be explained in terms of a simple analytical model. Let $I_B = L_B/\mu$ be the angular momentum per unit mass of the binary, with $\mu = M_1M_2/(M_1 + M_2)$ the reduced mass, and $I_* = L_*/m_*$ be the angular momentum per unit mass of a star interacting with the binary. Conservation of angular momentum during an encounter (assuming $m_* \ll M_1 + M_2$) gives

$$\Delta I_B \sim \frac{m_*}{\mu} \Delta I_*. \quad (2)$$

Considering that, once normalized per unit mass, the average change per encounter in the stellar angular momentum is of the order of the binary angular momentum (Merritt 2002), each interaction contributes, on average, a factor

$$\langle \Delta I_B \rangle \sim \frac{m_*}{\mu} I_B \quad (3)$$

to the binary angular momentum. The rate at which $I_B$ varies with time is

$$\frac{dI_B}{dt} = \frac{dn_{enc}}{dt} \langle \Delta I_B \rangle, \quad (4)$$

where $dn_{enc}/dt$ is the rate of binary/star interactions. The rate can be estimated as

$$\frac{dn_{enc}}{dt} = \pi n_* R_{enc}^2 v_{rel} \quad (5)$$

$$\approx \pi n_* \left( \frac{GM_2}{v_{rel}} \right)^2 v_{rel} \quad (6)$$

$$\approx \pi n_* \left( \frac{M_*}{M_1} \right)^2 \sqrt{GM_1a^3}, \quad (7)$$

where $n_*$ is the number density of stars in the cusp, $R_{enc}$ is the influence radius of the secondary hole and $v_{rel}$ is the mean relative velocity between the stars and $M_2$. Note that we have implicitly assumed that: (i) only stars efficiently interacting with the secondary modify the angular momentum of the binary and (ii) the dynamics outside the influence radius of the secondary is completely dominated by the primary.

In order to apply Eqs. 2–5, we need to specify the average direction of $\langle \Delta I_B \rangle$. This is opposite to the direction of the variation of the angular momentum of the star during the interaction. In a reference frame in which the $z$ direction is aligned with the total angular momentum of the cusp, the average $x$ and $y$ components of the angular momentum of the stars before an encounter are zero. In this simple model we assume that the final angular momentum of a star that experienced an interaction is isotropically distributed. This is justified by the observation that, at any time, stars after an interaction with the binary are much more isotropically distributed than before, as shown in Fig. 4 for the population of unbound stars. As a consequence, the variation $\langle \Delta I_B \rangle = \langle I_{z,1} - I_{z,0} \rangle$ points in the direction opposite to the angular momentum of the cusp $I_{cusp}$, and $\langle \Delta I_B \rangle_{enc}$, averaged over repeated encounters, points in the $z$ direction, parallel to $I_{cusp}$. The fast alignment that we observe in the $N$-body simulations is a direct consequence of such preferential direction
of $(\Delta l_B)$. Fig. 5 shows a schematic view of our model for different initial orientations of the binary.

The evolution of $\theta$ predicted by our model is shown with dotted lines in Fig. 3. Naturally, the case with $l_B$ aligned with $l_{\text{cusp}}$ does not show any evolution. Despite the simplifying assumptions made, the agreement between the initial evolution of $\theta$ in the runs and in the model is very good.

The predictions of the model and the results of the $N$-body runs disagree at late times. In the simulations, the binary stops reorienting well before perfect alignment is reached, while the model predicts $\theta \to 0$ asymptotically. This difference can be explained simply in terms of a depletion of stars in the centre of the cusp. As in many previous studies (e.g. Milosavljević & Merritt 2001; Milosavljević et al. 2002; Merritt 2006; Merritt, Mikkola & Szell 2007; Gualandris & Merritt 2011), we observe the formation of a central core due to slingshot ejections of stars. After a core has been excavated in the centre, the rate of encounters drastically drops and the evolution of the BHB’s orbital plane halts. This translates into a maximum angular momentum $l_{\text{max}}$ that can be transferred from the stars to the binary. Since in our model we assumed the transferred angular momentum to depend on the properties of the cusp and not on those of the binary (the stars are ejected isotropically), $l_{\text{max}}$ must be the same in every run. We computed the value of $l_{\text{max}}$ that needs to be transferred to the binary to match exactly the evolution of the $\theta_0 = 120^\circ$ run, and we checked if such a limiting angular momentum can account for the other runs’ behaviour. The results of this test are shown in Fig. 3 with dashed lines. The agreement with the $N$-body results is greatly improved by the introduction of a maximum angular momentum that can be transferred to the binary.

As a final note, we emphasize that the realignment in rotating cusps does not depend on the $m_*/M_{\text{BH}}$ ratio, as opposed to the non-rotating case. Since the rate of encounters under every assumption depends on the number density of stars, and the amount of angular momentum transferred per encounter is proportional to $m_*$, $dl_0/dt$ depends on the mass density $\rho$ of the cusp, but does not show any other dependence on $m_*/M_{\text{BH}}$. This is a consequence of the fact that the alignment in each encounter has a preferential direction (i.e. towards the angular momentum of the cusp). The upper panel in Fig. 2 shows the alignment $\Delta \theta$ experienced over a hardening time by binaries in rotating cusps, as a function of the number of stars in the cusp. Different lines are for different initial angles between $l_0$ and $l_{\text{cusp}}$. While in the non-rotating case the ratio between the realignments in the lowest and highest mass resolution runs is $\sim 30$, in this case the realignment shows only statistical fluctuations, with no systematic trends.

4 CONCLUSIONS

We studied the evolution of the orientation of the orbital plane of unequal-mass BHBs in isotropic and rotating stellar systems. The evolution in isotropic systems is characterized by a random walk on long time-scales, as predicted by Merritt (2002). The evolution in systems in which a fraction of stars is counter-rotating with respect to the binary was briefly discussed in Paper I. If the fraction of counter-rotating stars is small, the change in the orbital plane is consistent with the change expected for isotropic cusps. If, on the other hand, a large fraction of stars is counter-rotating, the plane of the binary evolves considerably and the binary angular momentum even reverses in the case of a fully counter-rotating cusp.

Here, we investigated for the first time the evolution of the binary plane in rotating systems in which the binary angular momentum is initially misaligned with respect to that of the stellar cusp. We find that misaligned binaries in rotating cusps tend to align their angular momentum with that of the cusp on a time-scale of a few hardening times. The alignment process is linear with time, hence, unlike the random walk observed in fully isotropic systems, does not depend on the mass ratio between the MBHs and the stars.

The realignment of the binary plane that we observe in the simulations may have significant implications. The direction of the spin axis of the single MBH that results from the merger of the holes due to emission of gravitational waves is affected by the orientation of the binary plane before coalescence. The spin axis, in turn, determines the orientation of the accretion disc around the remnant black hole via the Bardeen–Peterson effect (Bardeen & Petterson 1975) and, in radio-loud active galactic nuclei (AGNs), the direction of the radio jet.

After the coalescence of a BHB, the spin of the remnant $j_*$ is not necessarily aligned with the spins of the two progenitors, $j_1$ and $j_2$. If one of the two MBHs in the binary is radio-loud (and the remnant stays radio-loud), the change in the spin direction would result in a reorientation of the relativistic jet (Merritt & Ekers 2002). The orientation of the orbital plane of the binary has implications for the direction of $j_*$. The interaction with a rotating cusp tends to force the binary to co-rotate with the central cusp. At coalescence, the binary orbital angular momentum contribution to $j_*$ will result in a spin (and possibly a jet) preferentially aligned with the cusp angular momentum.

We do not expect full alignment, however, because: (i) the alignment we find in the simulations is not complete, and could halt in the absence of further refilling of stars or in the presence of isotropic refilling, leaving misalignment angles of up to $60^\circ$ and (ii) in a very gas-poor mergers. In gas-rich environments, gas accretion causes the spins of the MBHs to align with the angular momentum of the binary (Bogdanović, Reynolds & Miller 2007; Dotti et al. 2010; Kesden, Sperhake & Berti 2010; Volonteri, Gültekin & Dotti 2010), preventing any drastic change in the spins’ direction at coalescence.
unequal-mass binary (e.g. $q = 1/81$, like the one we study). $j$, depends strongly on $j_1$. Using the results of Rezzolla et al. (2008), if $j_1 \approx 1$, the angle between $j_1$ and $j_r$ is of only a few degrees. Realignment is more efficient for lower values of $j_1$: e.g. $j_1 \approx 0.1$ would result in an angle of $\geq 20^\circ$.

Such a preferential alignment is in fact observed. In weak radio-loud AGNs, Browne & Battye (2010) found a tendency for the axis of the radio emission to align with the minor axis of the starlight of the host, an oblate rotationally supported elliptical. In contrast, they found no preferred radio–optical alignment among the radio-louder objects (see also Saripalli & Subrahmanyan 2009) possibly hosted in triaxial non-rotating ellipticals (e.g. Kormendy et al. 2009).

ACKNOWLEDGMENTS

We thank Pau Amaro-Seoane and David Merritt for interesting discussions and the anonymous referee for useful comments on the manuscript.

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