The Evolution of a Supermassive Retrograde Binary in an Accretion Disk

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In this contribution we discuss the main results of a study of a massive binary with unequal mass ratio, q, embedded in an accretion disk, with its orbital rotation being opposed to that of the disk. When the mass ratio is sufficiently large, a gap opens in the disk, but the mechanism of gap formation is very different from the prograde case. Inward migration occurs on a timescale of $t_{ev} \sim M_p/\dot{M}$, where M_p is the mass of the less massive component (the perturber), and $\dot{M}$ is the accretion rate. When $q \ll 1$, the accretion takes place mostly onto the more massive component, with the accretion rate onto the perturber being smaller than, or of order of, $q^{1/3}M$. However, this rate increases when supermassive binary black holes are considered and gravitational wave emission is important. We estimate a typical duration of time for which the accretion onto the perturber and gravitational waves could be detected.

1 Statement of the problem

Supermassive black hole binaries (SBBH) may form as a consequence of galaxy mergers (see, e.g., [6, 1]). Since the directions of the angular momenta associated with the motion of the binary and the gas in the accretion disk are potentially uncorrelated, the binary may be on either a prograde or retrograde orbit with respect to the orbital motion in the disk when it becomes gravitationally bound and starts to interact with it. The prograde case has been considered in many works beginning with [3] and [2]. The retrograde case has received much less attention, with relatively few numerical simulations available to date (see, e.g., [7]). However, the retrograde case may be as generic as the prograde case when the interaction of SBBH with an accretion disk is considered. Note that although the disk is likely to be inclined with respect to the binary orbital plane initially, alignment on a length scale corresponding to the so-called alignment radius is attained relatively rapidly, the direction of rotation of the disk gas being either retrograde or prograde with respect to orbital motion, depending on the initial inclination (see, e.g., [3]). Here we briefly review recent results on the evolution of retrograde SBBH published in detail in [4].

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2 Numerical simulations of massive retrograde perturbers embedded in an accretion disk

In this section we consider numerical simulations for which the perturber is massive enough to significantly perturb the accretion disk and open a surface density depression called hereafter "a gap" in the vicinity of its orbit. For that we require mass ratio, q, of the perturber with mass M_p to the dominant mass M, to be larger than $\sim 1.57(H/r_p)^2$, where r_p is the radius of perturber's orbit and H is the disk semi-thickness. We consider values of $q = 0.01$ and 0.02 below. Note that the alternative case of a low mass perturber which is insufficiently massive to open a gap has been considered by [4]. The perturber was initiated on a retrograde circular orbit of radius r_0 which is taken to be the simulation unit of length. For simulation unit of time, we take the orbital period of a circular orbit with this radius, the disk aspect ratio was constant and equal to 0.05, for other details see [4]. The structure of the disk gaps for $q = 0.02$ is illustrated in the surface density contour plots presented in Fig. 1 at various times. Note that an animation of the process of gap formation can be found on the website *http://astro.qmul.ac.uk/people/sijme-jan-paardekooper/publications*. The semi-major axis is shown as a function of time for $q = 0.02$ and $q = 0.01$ with a gravitational softening length of $b = 0.1H$ and for $q = 0.01$ with $b = 0.6H$ in Fig. 2. The behavior depends only very weakly on whether the perturber is allowed to accrete from the disk or not.

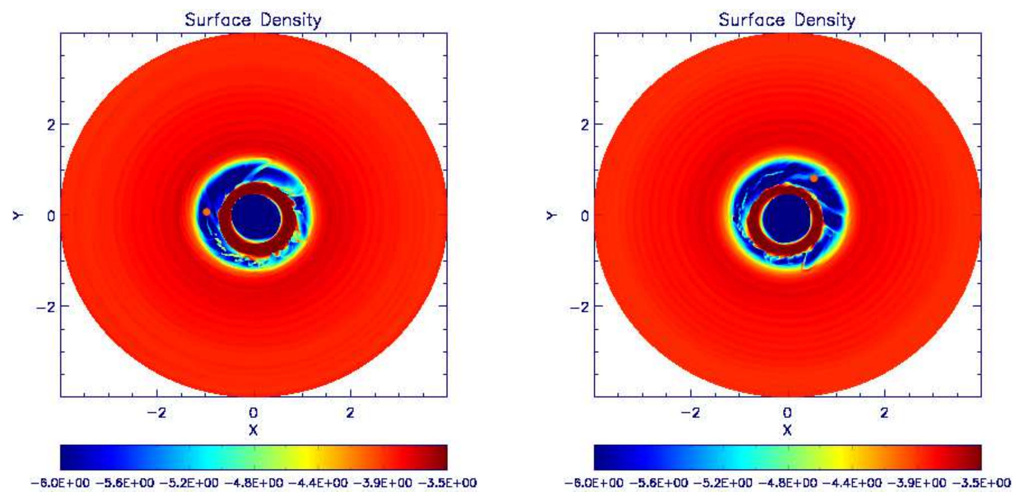

Figure 1: $\log \Sigma$ contours for $q = 0.02$ with softening length $0.1H$ after 50 orbits (left panel) and after 100 orbits (right panel). In these simulations the companion, its position in each case being at the center of the small red circle located within the gap region, was allowed to accrete. The width of the gaps slowly increases while the accretion rates, on average, slowly decrease with time. Short wavelength density waves in the outer disks are just visible. Note that values of $\log \Sigma$ below the minimum indicated on the color bar are plotted as that minimum value.

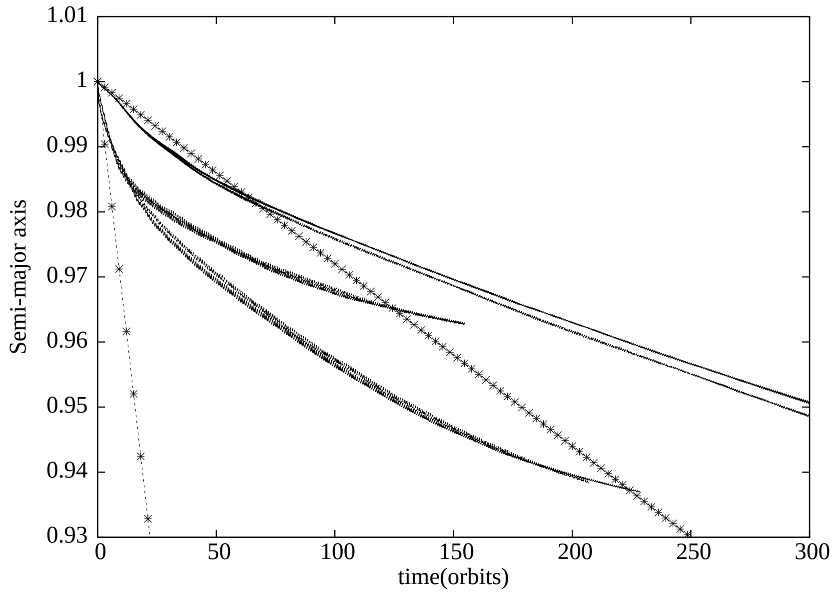

Figure 2: Semi-major axis, in units of the initial orbital radius, as a function of time for $q = 0.02$ and 0.01 with gravitational softening length $b = 0.1H$ and for $q = 0.01$ with $b = 0.6H$. Two curves without imposed crosses, which are very close together, are shown for each of these three cases. The uppermost pair of curves corresponds to $q = 0.01$ with $b = 0.6H$ and the lowermost pair to $q = 0.01$ with $b = 0.1H$. The central pair does to $q = 0.02$ with $b = 0.1H$. The lower of the pair of curves for the cases of $b = 0.1H$ corresponds to runs with accretion from the disk included. For the case of $b = 0.6H$, this situation is reversed. The straight lines which have imposed crosses are obtained adopting the initial Type I migration rate. The line with more widely separated crosses corresponds to $q = 0.01$ with $b = 0.1H$ while the other line corresponds to $q = 0.01$ with $b = 0.6H$.

3 Results

Our numerical results are confirmed by an analytic approach developed in [4]. In this paper the following general results have been obtained:

1) When the mass ratio q is small, but larger than $\sim 1.6(H/r_p)^2$ a gap in the vicinity of the perturber opens due to an increase of radial velocity of the gas in this region. Its size is smaller than the orbital distance r_p in this limit.
2) For such systems for which the perturber's mass is larger than a typical disk mass within a distance $\sim r_p$, the disk structure outside the gap is approximately quasi-stationary. The inner disk has nearly zero angular momentum flux, while the outer disk has an angular momentum flux equal to the product of the mass flux and the binary specific angular momentum. The orbital evolution timescale $t_{ev} = M_p/(2\dot{M})$ is then determined by conservation of angular momentum. Note that this picture differs from the prograde case with similar parameters, where there is a pronounced cavity instead of an inner disk and the orbital evolution is somewhat faster.

3) When the orbital evolution is determined by interaction with the disk, the mass flux onto the more massive component $\sim\dot{M}$, while the average mass flux onto the perturber is smaller $\sim q^{1/3}\dot{M}$. However, the latter exhibits strong variability on timescales on the order of the orbital period. The mass flux onto the perturber can increase significantly during the late stages of the inspiral of SBBH when the emission of gravitational waves controls the orbital evolution.
4) When the binary is sufficiently eccentric and the disk is sufficiently thin, the opening of a "conventional" cavity within the disk is also possible due to the presence of Lindblad resonances.

Additionally, we estimated a time duration for which the emitted gravitational waves would have sufficient amplitude for detection by a space-borne interferometric gravitational wave antenna with realistic parameters, as well as the appropriate range of frequencies as a function of the primary BH mass in [5].

Note that all these results have been obtained under the assumption that the binary orbit and the disk are coplanar. This may break down at late times. An estimate for the time required for their mutual inclination angle measured at large distances to change is given in [4] for an initially retrograde binary. The typical timescale is on the order of, or possibly even smaller than, t_{ev} depending on the mass ratio and disk parameters. Thus, this effect should be taken into account in future studies of these systems.

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* The color figure is available online in the Proceedings at *http://www.astro.spbu.ru/sobolev100/*.