Multiple black holes in galactic bulges

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ABSTRACT

We study the number and interaction rates of supermassive black holes in galactic bulges as predicted by hierarchical models of galaxy formation in which the spheroidal components of galaxies are formed by mergers. In bright ellipticals, the number of events that can eject a central supermassive binary black hole is large. Central binaries must therefore merge in less than a Hubble time – otherwise there will be too much scatter in the $M_\bullet - \sigma$ relation and too many off-center galactic nuclei. We propose that binary black holes are able to merge during the major gas accretion events that trigger QSO activity in galaxies. If this is the case, less than 10 percent of faint ellipticals and 40 percent of bright ellipticals are predicted to harbour binary black holes with near equal masses at their centres. This binary may be ejected away from the centre of the galaxy or even into intergalactic space in up to 20% of the most luminous ellipticals. The number of low mass black holes that can interact with the central object is predicted to be a strong function of galaxy luminosity. In most faint ellipticals, no black holes fall into the centre of the galaxy after the last major gas accretion event, but in the most luminous ellipticals, an average of 10 low mass black holes interact with the central supermassive object after this time. It is expected that stars will be ejected from galaxy cores as these low mass-ratio binaries harden. Multiple black holes in galactic bulges thus provide a natural explanation for the strong systematic trends in the observed central density profiles of ellipticals as a function of luminosity.

Key words: Black hole physics; Binaries:general; Galaxies:nuclei; Galaxies:formation

1 INTRODUCTION

According to the standard paradigm of structure formation in the Universe, galaxies merge frequently as their dark matter halos assemble. Frequent galaxy mergers will inevitably lead to the formation of supermassive binary black holes (e.g. Milosavljevic & Merritt 2001). It is not clear if these supermassive binaries will be able to merge on a Hubble time (Begelman, Blandford & Rees 1980; Milosavljevic & Merritt 2001; Yu 2002). If merging timescales are long, the binary is likely to interact with new infalling black holes through gravitational slingshot interactions (Saslaw, Valtonen & Aarseth 1974). There is some circumstantial observational evidence that binary black holes do merge (e.g. Merritt & Ekers 2002), but very little is known about the rate at which these mergers occur.

A number of authors have presented models for the growth of supermassive black holes in merging galaxies in a cold dark matter (CDM) Universe (Cattaneo, Haehnelt & Rees 1999; Kauffmann & Haehnelt 2000 (KH2000); Monaco, Salucci & Danese 2000; Menou, Haiman & Narayanan 2001; Heinänenki 2001; Volonteri, Haardt & Madau 2002, Cattaneo 2002). Here, we extend the models of KH2000, which explicitly followed the star formation histories and dynamical evolution of bulges. In a subsequent paper, Haehnelt & Kauffmann (2000) demonstrated that the same model could also reproduce the observed $M_\bullet - \sigma$ relation (Gebhardt et al. 2000, Ferrarese & Merrit 2000). KH2000 made the extreme assumption that black holes merge instantaneously when a bulge forms through a merger of two galaxies of roughly equal mass. In this Letter we relax this assumption and we discuss some of the issues which will influence our predictions of the multiplicity of black holes in galactic bulges. We also explore the possibility that the merging of supermassive binary black holes in bright ellipticals is responsible for the observed cusp/core dichotomy of elliptical galaxies (Gebhardt et al. 1996; Merritt 2001).

2 THE BUILD-UP OF SUPERMASSIVE BLACK HOLES IN KH2000

In the model of KH2000, spheroids form when two galaxies of comparable mass merge. The central black holes of the progenitor galaxies are assumed to coalesce instantaneously and a fraction of the available cold gas is accreted.
The amount of cold gas in galaxies is determined by the balance of cooling, star formation and “feedback” by supernovae. The fraction of the available cold gas accreted by the black hole is assumed to scale with the circular velocity $v_{\text{circ}}$ of the surrounding dark matter halo. Note that in the models, the mass accretion rate often exceeds the Eddington rate at high redshifts.

Figure 1 shows a typical accretion and merging history of the central black hole in the remnant of a merger (present-day luminosity $M_V = 22.9$). The amount of cold gas accreted by the black hole is assumed to scale with the circular velocity $v_{\text{circ}}$ of the surrounding dark matter halo. Note that in the models, the mass accretion rate often exceeds the Eddington rate at high redshifts. Initially, when low angular momentum stellar orbits are still populated, the binary will harden quickly. If all three black holes have similar masses, the kick velocity will be sufficient to kick the binary into the outer parts of the galaxy or even to eject it entirely (see Hut & Rees 1992 for a discussion). The accretion of gas can in principle reduce the binary separation on a much shorter timescale if the accreted gas mass exceeds that of the binary but it is uncertain how efficiently this process operates.

3 MULTIPLE BLACK HOLES

3.1 Formation and merging of binary black holes

When two galaxies merge, the smaller galaxy will sink to the centre of the merger remnant because of dynamical friction. The outer regions of the infalling galaxy will be gradually tidally stripped in the process. If two galaxies with roughly equal mass merge, a binary black hole will form within a few dynamical times (Milosavljević & Merritt 2001). If the mass ratio between the two galaxies is large, the time it takes for the infalling galaxy to reach the center of the remnant also becomes large and may exceed the Hubble time. In practice, the timescale for the formation of the binary will depend not only on the mass ratio of the galaxies, but also on the density profiles of the merging galaxies and the orbital parameters of the infalling galaxy.

The subsequent evolution of the supermassive binary has been discussed by Begelman, Blandford & Rees (1980). For an initially circular orbit coalescence within time $T$ occurs when the velocity of the orbit $v_{\text{orb}}$ reaches

$$v_{\text{orb}} \sim v_{\text{gr}} \sim 2600 \left( \frac{m_{\text{prim}} + m_{\text{sec}}}{10^9 M_\odot} \right)^{1/8} \left( \frac{m_{\text{sec}}}{m_{\text{prim}}} \right)^{-1/8} \left( \frac{T}{10^{10} \text{yr}} \right)^{-1/8} \text{km s}^{-1},$$

where $m_{\text{prim}}$ and $m_{\text{sec}}$ are the mass of the primary and secondary black holes (Peters 1964, Gould & Rix 2000). It is uncertain whether stellar-dynamical processes will be able to reduce the separation of the binary so that coalescence by emission of gravitational waves will occur in less than a Hubble time.

The binary is expected to harden either by gravitational slingshot ejection of stars (Quinlan 1996, Milosavljević & Merritt 2001) or by the accretion of gas onto the binary system (Armitage & Natarajan 2002). The timescale for the ejection of stars to cause the binary to harden will exceed the Hubble time in bright galaxies unless stars are scattered into low-angular momentum orbits more efficiently than by star-star relaxation (see Zhao, Haehnelt & Rees 2002 for some suggestions how that may be achieved) or the central regions of galaxies are sufficiently triaxial (Begelman, Blandford, & Rees 1980, Yu 2002).

The accretion of gas can in principle reduce the binary separation on a much shorter timescale if the accreted gas mass exceeds that of the binary but it is uncertain how efficiently this process operates.

3.2 Mergers of equal mass black holes and the expected binary fraction

After a hard binary has formed with a circular velocity larger than the stellar velocity dispersion of the galaxy, the infall of a third black hole will normally lead to gravitational slingshot ejection of the lightest black hole with a velocity of around one third of the relative orbital velocity of the binary black hole (Saslaw et al. 1974, Hut and Rees 1992). The binary will also get a kick velocity that is smaller than the velocity of the ejected black hole by a factor $m_{\text{ej}}/m_{\text{bin}}$. The time evolution of the hardening is uncertain and it is difficult to predict what the orbital velocity of the supermassive binary is likely to be for a typical slingshot ejection.

Initially, when low angular momentum stellar orbits are still populated, the binary will harden quickly. If all three black holes have similar masses, the kick velocity will be sufficient to kick the binary into the outer parts of the galaxy or even to eject it entirely (see Hut & Rees 1992 for a discussion).

The dashed line in Figure 2 shows the distribution of the number of black hole mergers in elliptical galaxies with mass ratios $m_{\text{sec}}/m_{\text{prim}} > 0.3$. Results are shown for a range of bulge luminosities. The median number of mergers increases from one in faint bulges to three in bright bulges. Figure
Figure 2. The distribution function of the number of black hole mergers with mass ratios \( m_{\text{sec}}/m_{\text{prim}} > 0.3 \). Results are shown for galactic bulges with different V-band luminosities. The dashed histogram shows the total number of possible black hole mergers. The solid histogram is the number of mergers after the last major gas accretion event, in which the accreted gas mass exceeds the sum of the masses of the two black holes in the merging galaxies.

Figure 3. As in figure 2, except for black hole mergers with mass ratios \( m_{\text{sec}}/m_{\text{prim}} > 0.01 \). The mass ratio of the two merging galaxies has also been constrained to be larger than 0.01. Dashed histogram is the total number of mergers in the model. The solid histogram is the number of mergers after the last major gas-rich accretion event.

2 demonstrates that if the merging timescale of supermassive binary black holes is longer than the Hubble time, a binary should be ejected in up to 40 percent of bright elliptical galaxies. This would appear to conflict with the fact that black holes are observed in all nearby bright elliptical galaxies and with the tightness of the observed \( M_{\bullet} - \sigma \) relation. This strongly supports the hypothesis that the merging timescale of supermassive binaries is shorter than the Hubble time (Zhao et al. 2002, Merritt & Ekers 2002).

The solid line in Figure 2 shows the distribution of the number of mergers after the last accretion event in which the mass of accreted gas exceeded the sum of the masses of the two black holes in the binary system. The median number of mergers since this event ranges from zero in faint galaxies to one in bright galaxies. If the supermassive black holes do indeed merge during gas-rich accretion events, the fraction of elliptical galaxies containing large mass ratio binary black holes will not be larger than 10% in faint ellipticals and 40% in brighter objects. The fraction of galaxies with a third massive “intruder” ranges from 0 to 20 percent. Binary black hole ejections will then only occur in a small fraction of only the brightest galaxies.

3.3 Unequal mass mergers and the core/cusp dichotomy of elliptical galaxies

Observed bulges show a clear dichotomy in their central density profiles. Faint galaxies have steep inner density profile which are close to isothermal \((\rho \propto r^{-\gamma}), \gamma = 2\) while bright galaxies have significantly shallower core profiles \((\gamma \lesssim 1)\). There is a transition from cusp to core profiles at a V-band luminosity of around -20 (Gebhardt et al. 1996). Some bright galaxies even show indications of a decreasing stellar density at their centres (Lauer et al. 2002).

It has been argued that the growth of supermassive black holes may affect the central stellar density profile of galactic bulges beyond the radius where the black hole dominates the gravitational potential. Even the sign of the effect remains controversial, however. Adiabatic growth of a single black hole would lead to a steepening of the density profile (van der Marel 1999), while binary hardening due to stellar dynamical interactions will deplete the central regions and lead to a flattening of the density profile (e.g. Merritt 2001, Milosavljevic & Merritt 2001). Quinlan (1996) studied the hardening of supermassive binary black holes and found that small mass ratio binaries eject stars nearly as efficiently as large mass ratio binaries. This suggests that the total number of mergers may determine the ejected mass. Ravindranath et al (2002) and Milosavljevic et al. (2002) assumed that the density profiles of elliptical galaxies are always initially steep and calculated the mass in stars that would have to be ejected from the centre in order to explain the observed profiles of bright ellipticals. They found a strong non-linear correlation between the observed black hole mass and the ejected mass. The ejected mass is larger than the black hole mass by a factor of a few.

It is not understood, however, why there is a dichotomy in profile shape between bright and faint galaxies. It is also not clear whether black holes merge frequently enough to eject a few times the mass of the binary. In Figure 3 we show the number of black hole mergers with mass ratios \( m_{\text{sec}}/m_{\text{prim}} > 0.01 \) that occur after the last major gas accretion event. Van den Bosch et al. (1999) studied the sinking of DM satellites within DM haloes and found that for orbits with moderate ellipticities (0.3-0.5) the timescale to
reach the centre approaches the Hubble time for mass ratios smaller than 0.01. The situation may not be exactly analogous for mergers of galaxies rather than dark matter halos, because the density profiles of galaxies are different and they also contain gas. Nevertheless, in order to exclude black holes that may take more than a Hubble time to reach the centre of the parent galaxy, we only count mergers with $m_{\text{sat}}/m_{\text{prim}} > 0.01$. The median number of such minor mergers increases from 0 for faint ellipticals to 10 for the brightest systems. More than 50% of galaxies fainter than $M_V = -20$ do not experience any black hole mergers, while the mean/median number of mergers rises strongly for galaxies brighter than $M_V = -20$ (Fig. 4).

The relation between the total number of mergers and the actual ejected mass is uncertain. In order to predict the ejected mass, we would need to know the relaxation time scale on which low angular momentum orbits are repopulated and the detailed orbital structure of the central part of elliptical galaxies. Nevertheless our results show that there is a strong dependence of the total number of mergers on galaxy luminosity and this may well explain the core/cusp dichotomy of elliptical galaxies. The large ejected masses in bright galaxies would require efficient hardening in 5 to 10 merging events.

4 CONCLUSIONS

According to hierarchical merger models, the formation of supermassive binary black holes will be common. Unless the majority of these binaries merge faster than a Hubble time, further infall of new black holes will lead to an ejection rate of these binary systems that is too large to be consistent with the small scatter in the $M_\bullet - \sigma_*$ relation. There is also no observational evidence for the existence of a significant fraction of galaxies with off-centre galactic nuclei. The accretion of gas and binary hardening by stars are the two main candidates for driving the merger of these binaries. We have assumed that the former is efficient if the accreted gas mass exceeds the total mass of the supermassive binary. This reduces the fraction of faint ellipticals with binary black holes to less than 10% and the fraction of bright galaxies that harbour binaries to less than 40%. Up to 20% of the brightest ellipticals have recently ejected a binary from their centres. We thus predict that a small fraction of bright ellipticals do not contain a central black hole with a mass that fits onto the $M_\bullet - \sigma_*$ relation. We note, however, that the fraction of binaries that are truly ejected from the galaxy depends sensitively on the time evolution of the hardening and on the detailed orbital structure at the centre of galactic bulges. Gas accretion in cooling flows may also prevent efficient binary ejection.

Finally, we have demonstrated that the total number of expected low mass ratio black hole mergers is a strong function of bulge luminosity. A strong transition from no mergers to many mergers occurs at the same characteristic luminosity ($M_V = -20$) where ellipticals transition from cuspy to core-dominated central profiles. This supports the hypothesis that the ejection of stars by central supermassive binary black holes is indeed responsible for the shallow central density profiles observed in luminous elliptical galaxies.

REFERENCES

Armitage P., Natarajan P., 2002, ApJ, 567, L9
Begelman M., Blandford R., Rees M.J., 1980, Nature, 287, 307
Cattaneo, A., Haehnelt, M.G. & Rees, M.J., 1999, 308, 77
Cattaneo, A., 2002, MNRAS, 333, 353
Ferrarese L., Merritt D., 2000, ApJ, 539, L9
Gebhardt K., Richstone D., Ajhar, E.A., Lauer T.R., Byun Y.-I., Kormendy J., Dressler A., Faber S. M., Grillmair C., Tremaine S., 1996, AJ, 112, 105
Gebhardt K., Bender R. Bower G., Dressler A., Faber S.M., Filipenko A.V., Ho L.C., Kormendy J., Lauer T.R., Magorrian J., Pinkney J., Richstone D., & Tremaine S., 2000, ApJ, 539, L13
Gould A., Rix H.-W., 2000, ApJ, 532, L32
Haehnelt M.G., Kauffmann G., 2000, MNRAS, 318, L35
Heinämäki P., 2001, A&A, 391, 795
Hut P., Rees M.J., 1992, 259, 27
Kauffmann G., Haehnelt M.G., 2000, MNRAS, 311, 576 (KH2000)
Lauer et al., 2002, submitted to AJ
Menou K., Haiman Z., Narayan V.K., 2001, ApJ, 558, 535
Merritt D., Ekers R., 2002, Science, vol. 297, August 1
Merritt D., 2000, in "Galaxy Dynamics: From the Early Universe to the Present", 15th IAP July 9-13 1999, eds. F. Combes, G. Mamon and V., ASP conference series, Vol 197, p. 221
Milosavljević, Merritt D., 2001, ApJ, 563, 34
Milosavljević, Merritt D., Rest A., van den Bosch F.C., 2002, 331, L51
Monaco P., Salucci P., Danese L., 2000, MNRAS, 311, 279
Peters P.C., 1964, Phys. Rev. B., 136, 1224
Quinlan G.D., 1996, New Astronomy, 1, 35
Ravindranath S., Ho L.C., Filipenko A.V., 2002, ApJ, 566, 801
Saalaw W.C., Valtonen M.J., Aarseth S.J., 1974, ApJ, 190, 253
van den Bosch, F.C., Lewis G.F., Lake G., Stadel J. 1999, ApJ, 515, 50
van der Marel R. P., 1999, AJ, 117, 744
Volonteri M., Haardt F., Madau, P., 2002, submitted, astro-ph/0206122
Yu Q., 2002, MNRAS, 331, 953
Zhao H., Haehnelt M.G. & Rees, 2002, NewA, 7 385