The Final Parsec: what happens to supermassive black holes during major galaxy mergers

1a. Summary

In this project we will study what happens to the supermassive black holes in the central regions of galaxies throughout the process in which two galaxies merge. Our theoretical understanding of the circumstances under which supermassive black holes (SMBHs) coalesce is very poorly developed. Observations indicate that they must coalesce but the theory is inconclusive, especially how the holes cover the final parsec before merging.

It is essential that this conundrum between theory and observations is solved because our understanding of the formation of large scale structure in the universe is based upon merging of large galaxies, which again drives the engines of galactic nuclei and the growth of SMBHs. In addition, understanding the merging of SMBHs is important for testing general relativity as they form a major contribution to low-frequency gravitational waves that can be detected by the Laser Interferometer Space Antenna. A profound understanding of these processes is also crucial to further develop our knowledge of the non-linear dynamics at the center of our own Galaxy and its spectrum of physical phenomena which has been perplexing astronomers for the last decades: the origin of the young stars in the inner milliparsec and the acceleration of stars to speeds so high that they escape the Galaxy.

I will make significant progress in our understanding of galaxy mergers and the subsequent coalescence of their SMBHs by modelling interacting galaxies at unprecedented resolution. This must be done numerically using models that incorporate a broad range of physical phenomena. This proposal capitalizes on the rapid expansion of computational astrophysics, and the recent progress that has been made on multi-scale and multi-physics simulations using hybrid architectures on distributed computers. It will continue and expand the unique expertise of my group in this field, exemplified by its leading role in several important international collaborations.

Keywords: GALAXY DYNAMICS AND EVOLUTION; GRID COMPUTING; HIGH-PERFORMANCE COMPUTING; MULTI-SCALE COMPUTING; SUPER-MASSIVE BLACK HOLES;

2 Research proposal

2a. Objective

Galaxies are the visible building blocks of the Universe. As the Universe continues to expand, galaxies cluster together due to their mutual gravitational attraction, to eventually participate in frequent mergers. These processes drive the evolution of large scale structure and the morphological evolution of galaxies.

Each major galaxy is observed to host a supermassive black hole (SMBH), which is a million to several billion times more massive than the Sun [1]. When two galaxies merge they form one larger galaxy and the two SMBHs form a binary in its center, which are expected to coalesce soon afterwards [2].

This hierarchical merging process is supported by the observed relation in which more massive galaxies host more massive black holes [3, 4], and that most binary SMBHs are observed in galaxies which are in the process of merging but rarely in single galaxies. Galaxy mergers are therefore expected to drive the growth of SMBHs [5].

The basic relation between the morphological evolution of galaxies and the growth of their SMBHs is strongly supported by observations, but a fundamental theoretical understanding of the process is missing, leaving the observations unexplained. Within a cosmological context we understand how SMBHs approach each other from a distance of millions of parsecs[1] to about

[1]One parsec is about 3.3 light years.

one parsec, but not how they get any closer. This fundamental problem called *the final parsec problem*, is unsolved to-date.

The main problem in the theoretical arguments as well as in the numerical simulations is hidden in the conjecture that galaxy mergers could be studied independently of SMBH coalescence. This artificial decomposition between macroscopic phenomena and microscopic processes was motivated by the lack of self-consistent models and limited resources.

My extensive expertise in self-consistent simulations of dense stellar systems over the appropriate range of time scales and sizes combined with my experience in building and using specialized computer hardware, grid technology and hybrid computer architectures gives me a unique perspective which enables me to overcome these problems.

2b. Approach

To simulate a merger between two galaxies and follow the subsequent coalescence of the two SMBHs it is necessary to resolve the large scale structure of both galaxies, their dark matter halos, bulges and the detailed dynamics of both black holes, all at once and self consistently. This is a challenge since the range in size and time scales exceeds the standard precision of modern computers and the necessary computational power is enormous. To overcome these challenges I propose to develop a hybrid simulation environment for modelling galaxy mergers.

The adopted numerical method will change in a number of discrete steps, depending on local conditions. The overall structure of both galaxies and their dark matter halos will be addressed using a Lagrangian Smoothed Particle Hydrodynamics (tree-SPH) technique [6], which is perfectly suited for integrating the equations of motion of the stars in low-density environments (the dark matter halo and the galactic disc) and the gas (mainly in the disc). This method is sufficiently fast to simulate a large number of particles and it is sufficiently accurate to capture the relevant physics in the low density regions of the galaxies.

In the high-density regions (the sphere of influence of the SMBHs) we adopt the direct N-body technique, which is accurate but slow. Luckily the number of stars in this regime hardly exceeds a million. While this is still a large number of stars to integrate by direct summation, it is doable with the proper algorithms, efficient parallelization and by deploying specialized hardware.

Stars in the Keplerian region of the SMBHs will be treated with algorithmic regularization [7] and the innermost milliparsecs, where general-relativistic effects become apparent, are integrated using post-Newtonian corrections up to 2.5-th order [8].

2c. Innovation

All simulations of galaxy mergers performed so far had insufficient resolution for properly treating the inner parts where the SMBHs reside. On the other hand, simulations of SMBH mergers missed the context and the dynamics of the surrounding environment. By combining methodologies for resolving the global structure of galaxy mergers and the microscopic details for the inner regions, we will be able to study the microscopic as well as the macroscopic aspects of galaxy mergers simultaneously. This was not done before.

The required computer power and the hybridization of numerical solvers, tree-SPH, direct N-body, arithmetic regularization and the post-Newtonian treatment poses unique challenges for computational science. Each solver is executed most efficiently on a different computer architecture, which makes the range of numerical solvers unsuited for a single computer; running the hybrid software environment implies the use of a grid infrastructure [9]. The tree-SPH code, for example, runs most efficiently on a parallel cluster with graphical processing units [10, 11], whereas the direct N-body solver runs best on specialized hardware [12]. The latency and bandwidth characteristics of these simulations pose no serious communication bottle-neck, even when considering long-baseline computing [13].

2d. Research plan

There are three main parts to the project. The starting point is the construction of a computer cluster and initiation of a virtual organization with sufficient capacity to perform the calculations.

Subproject A: The primary objective of this subproject is to simulate the mergers of galaxies with sufficient resolution to resolve the moment that the SMBHs form a hard binary (at a separation of about a parsec). We will develop a hybrid N-body code in which the low-density regions of the galaxy (the halo and the bulge) are simulated using the tree-SPH technique, whereas the high-density regions near the SMBHs are simulated using the direct N-body method. While studying galaxy mergers, this subproject is also tailored to studying the morphological characteristics of galaxy mergers in the Toomre sequence [14, 15].

Two additional people (1 Post-doc and 1 PhD student) will support the development of this simulation tool. They will work on the two main aspects of the code development and carry out extensive simulations to understand the physics of galaxy mergers.

Subproject B: The aim of this subproject is to simulate the final stage of the merger between the two bulges and their SMBHs. The key element will be to understand the dynamics in the sphere of influence of the two orbiting black holes; how they evolve from a hard binary up to the moment they coalesce due to the emission of gravitational waves. Apart from studying the final phase of SMBH coalescence, this subproject is also tailored to studying the stellar cusp around SMBHs [16], the consequences of intermediate-mass black holes [17], the origin of the young stars orbiting the SMBH in the Galactic center and the production of hyper-velocity stars [18].

Two additional people (1 Post-doc and 1 PhD student) will support the development of this simulation tool and carry out the proposed research of studying SMBH mergers.

Subproject C: In this subproject we plan on building a parallel computer with Graphical Processing Units (GPUs), and to connect this cluster to our intercontinental GRAPE grid [19, 9], which is part of the DAS-3 national grid infrastructure. By attaching GPUs to workstations we gain the flexibility, communication characteristics and the raw super-computer power required for the large scale simulations proposed in subprojects A and B.

One additional person (1 programmer/postdoc) will support the construction and development of the hardware environment for performing the hybrid simulations on a grid of specialized and semi-dedicated hardware.

2e. Literature references for the proposal

References

[1] Kormendy, J., Richstone, D.: Inward Bound—The Search For Supermassive Black Holes In Galactic Nuclei. ARA&A **33** (1995) 581–+

[2] Yu, Q., Tremaine, S.: Observational constraints on growth of massive black holes. MNRAS **335** (2002) 965–976

[3] Gebhardt, K., Bender, R., Bower, G., Dressler, A., Faber, S.M., Filippenko, A.V., Green, R., Grillmair, C., Ho, L.C., Kormendy, J., Lauer, T.R., Magorrian, J., Pinkney, J., Richstone, D., Tremaine, S.: A Relationship between Nuclear Black Hole Mass and Galaxy Velocity Dispersion. ApJL **539** (2000) L13–L16

[4] Merritt, D., Ferrarese, L.: The M_{BH}-σ Relation for Supermassive Black Holes. ApJ **547** (2001) 140–145

[5] Johansson, P.H., Naab, T., Burkert, A.: Equal- and unequal-mass mergers of disk and elliptical galaxies with black holes: The M_BH-sigma and M_BH-M_* relations. ArXiv e-prints **802** (2008)

[6] Monaghan, J.J.: Smoothed particle hydrodynamics. ARA&A **30** (1992) 543–574

[7] Mikkola, S., Merritt, D.: Algorithmic regularization with velocity-dependent forces. MNRAS **372** (2006) 219–223

[8] Mikkola, S., Merritt, D.: Implementing Few-Body Algorithmic Regularization with Post-Newtonian Terms. ArXiv e-prints **709** (2007)

[9] Groen, D., Portegies Zwart, S., McMillan, S., Makino, J.: Distributed N-body simulation on the grid using dedicated hardware. New Astronomy **13** (2008) 348–358

[10] Portegies Zwart, S.F., Belleman, R.G., Geldof, P.M.: High-performance direct gravitational N-body simulations on graphics processing units. New Astronomy **12** (2007) 641–650

[11] Belleman, R.G., Bédorf, J., Portegies Zwart, S.F.: High performance direct gravitational N-body simulations on graphics processing units II: An implementation in CUDA. New Astronomy **13** (2008) 103–112

[12] Makino, J., Taiji, M.: Scientific simulations with special-purpose computers : The GRAPE systems. Scientific simulations with special-purpose computers : The GRAPE systems /by Junichiro Makino & Makoto Taiji. Chichester ; Toronto : John Wiley & Sons, c1998. (1998)

[13] Hoekstra, A., G., Portegies Zwart, S., Bubak, M., Sloot, P.: Towards Distributed Petascele Computing. Petascale Computing: Algorithms and Applications, by David A. B ader (Ed.). Chapman & Hall/CRC computational science series 565pp. (2008)

[14] Toomre, A., Toomre, J.: Galactic Bridges and Tails. ApJ **178** (1972) 623–666

[15] Toomre, A.: Mergers and Some Consequences. In Tinsley, B.M., Larson, R.B., eds.: Evolution of Galaxies and Stellar Populations. (1977) 401–+

[16] Bahcall, J.N., Wolf, R.A.: Star distribution around a massive black hole in a globular cluster. ApJ **209** (1976) 214–232

[17] Baumgardt, H., Gualandris, A., Portegies Zwart, S.: Ejection of Hyper-Velocity Stars by Intermediate-Mass Black Holes. Journal of Physics Conference Series **54** (2006) 301–305

[18] Gualandris, A., Portegies Zwart, S.: A hypervelocity star from the Large Magellanic Cloud. MNRAS **376** (2007) L29–L33

[19] Foster, I., Kesselman, C., Tuecke, S.: The Anatomy of the Grid: Enabling Scalable Virtual Organizations. "International Journal of High Performance Computing Applications" **15** (2001) 200