The MODEST questions: challenges and future directions in stellar cluster research

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Abstract

We present a review of some of the current major challenges in stellar cluster research, including young clusters, globular clusters, and galactic nuclei. Topics considered include: primordial mass segregation and runaway mergers, expulsion of gas from clusters, the production of stellar exotica seen in some clusters (eg blue stragglers and extreme horizontal–branch stars), binary populations within clusters, the black–hole population within stellar clusters, the final parsec problem, stellar dynamics around a massive black hole, and stellar collisions. The *Modest Questions* posed here are the outcome of discussions which took place at the Modest-6A workshop held in Lund, Sweden, in December, 2005. Modest-6A was organised as part of the activities of the *Modest Collaboration* (see www.manybody.org for further details).

1 Introduction

MODEST is an abbreviation for MOdeling DEnse STellar systems, and is a collaboration between groups working throughout the world on stellar cluster research, including both theoreticians and observers. The Modest-6A workshop was held in Lund, Sweden, in 2005, as part of the continuing activities of the Modest Collaboration. A particular task of this workshop was to produce a list of challenges in stellar cluster research – *The Modest Questions* – considering both problems likely to be solved in the shorter term (around one year) and those requiring more work (timescales of several years). This paper provides a review of what came out of the discussion at Modest–6A. The

topics have been grouped into three areas (young clusters, globular clusters, and galactic nuclei) although there is naturally some overlap between the three sections.

2 Young Clusters

2.1 Primordial mass segregation and runaway mergers

Dynamical interactions between stars in young clusters leads to mass segregation, in which the heavier stars sink towards the cluster centres (Bonnell & Davies, 1998; de Grijs et al., 2002; Kroupa, 2004; Fleck et al., 2006). This occurs very rapidly, on a timescale of roughly $t_{\mathrm{mseg}} \approx t_{\mathrm{relax}} m_{\mathrm{av}}/m_{\mathrm{heavy}}$, where t_{relax} is the two-body relaxation time of the cluster and $m_{\mathrm{av}}, m_{\mathrm{heavy}}$ are the average stellar mass and the mass of the heavy stars; t_{mseg} may approach the crossing time for very young dense clusters. However, clusters may *form* in a mass-segregated state by the competitive accretion process outlined in Bonnell et al. (1997). Whether or not mass segregation is a primordial state of star clusters is a crucial question because it affects the timescale for core collapse and it also has some bearing on the origin of massive stars. This in turn affects the process of mergers involving massive stars in cluster cores. A cluster which is intially mass-segregated is more likely to undergo a runaway merger process, since the massive stars are already situtated at the cluster centre.

In a star cluster where the two-body relaxation time is sufficiently small ($t_{\mathrm{relax}} \lesssim 100\,\mathrm{Myr}$) the most massive stars can reach the cluster core by dynamical friction and drive the cluster to a state of core collapse before they explode (Portegies Zwart & McMillan, 2002a; Gürkan et al., 2004; Freitag et al., 2005). During this phase the stellar number density in the cluster core becomes so high ($n_c \gtrsim 10^8\,\mathrm{stars/pc^3}$) that stars may experience direct physical collisions. This may lead to a runaway collision process in which one star repeatedly collides with other stars (Portegies Zwart et al., 1999). The growth rate of this object may exceed $10^{-3}\,\mathrm{M_\odot/yr}$, and can therefore exceed the stellar mass loss rate, which for the most massive stars is of the same order (Vink et al., 2001). The mass of the single massive object may grow to about 1000–$3000\,\mathrm{M_\odot}$ although the subsequent evolution of this object is unclear; it may for example collapse to form a black hole (Portegies Zwart et al., 2004). Observations may tell us whether or not such intermediate mass black holes form in dense stellar clusters. Good candidates so far are the young and dense star cluser MGG-11 in the starburst galaxy M82 (McCrady et al., 2003), and the stellar conglomerate IRS13E very near the Galactic center (Maillard et al., 2004). The latter object is of particular interest as its black hole may be of the order of $1500\,\mathrm{M_\odot}$ to $15000\,\mathrm{M_\odot}$ (Schödel et al., 2005). The subject of intermediate-mass black holes within globular clusters will be discussed in section 3.7.

For the MODEST questions and tasks on this subject, we propose:

- In the next year: perform N-body simulations of clusters with and without primordial mass segregation to determine its effect on the evolution of the clusters, particularly in regard to core collapse and runaway mergers.

- In the next three to ten years: Do any mass–segregated systems exist which are too young to have segregated dynamically (Gouliermis et al., 2004)?

- In the next ten years: How do winds and instabilities affect the evolution of massive stars and what implications does this have for the behaviour of very massive merger products?

2.2 Gas expulsion from clusters

Embedded clusters represent a crucial but poorly-understood phase in the process by which a giant molecular cloud is converted to a population of stars (Dale et al., 2005; Clark et al., 2005). The observation that most embedded clusters do not survive to become open or globular clusters (Lada & Lada, 2003) implies either that most embedded clusters become unbound during the star-formation process, or that the giant molecular clouds from which they form were never bound in the first place (Elmegreen, 2000).

There are essentially three types of embedded systems (Kroupa & Boily, 2002): *Type I* contain from a few to 1000 stars but no O stars since they are too rare to be sampled from the IMF. *Type II* have between about 10^3 and 10^5 stars and contain between a few to about one hundred O stars. *Type III* clusters are massive with $\gtrsim 10^5$ stars. Gas-expulsion may take a few crossing times for type I clusters because the cumulative feedback energy from low-mass stars drives the gas out. For type II clusters gas expulsion may be explosive because the O stars provide sufficient feedback energy to blow out the gas on a crossing timescale or shorter. In the very massive type III systems, feedback from O-stars is likely to be insufficient to remove gas until the detonation of the first supernovae because the gas density in these systems is large enough to quench the effects of photoionisation and winds. Such massive systems can therefore achieve core collapse while still containing substantial quantities of gas and therefore modelling them poses a particularly difficult problem as one must allow for both the dynamical N-body and hydrodynamical evolution of the system.

The efficiency with which feedback expels gas determines the star-formation efficiency and also the likelihood of the cluster becoming unbound: a cluster unbinds more readily for low star formation efficiencies and/or for gas expulsion timescales shorter than a crossing time (Lada et al., 1984; Goodwin, 1997). It is therefore important to model this process correctly. Gas expulsion also converts a hydrodynamical problem into an N-body problem, and thus determines when N-body calculations may start (Geyer & Burkert, 2001; Kroupa et al., 2001). At present, stellar feedback is poorly understood because it is not possible to treat directed outflows self-consistently, nor is it possible to handle the full radiative transport problem in three dimensions.

We propose the following MODEST questions and tasks:

- In the next one to three years: creation of a hybrid N-body SPH code, using high-precision N-body codes such as NBODY6 or `starlab` as a starting point, since most existing hybrid codes are SPH codes which have had an N-body component grafted on.

- In the next ten years: What is the efficiency with which O-stars expel gas from typical clusters and hence what is the typical efficiency of star-formation?

- In the next ten years: study the formation of a $10^6 M_\odot$ cluster from the collapse of its natal molecular cloud until the stage in cluster evolution where mass loss becomes dominated by stellar evolution

2.3 Cluster complexes

It has been recognized for some time that studying the formation of isolated stars does not paint a realistic picture of star formation, since virtually all stars form in clusters and many interact with each other during their formation. There is also a considerable body of evidence that cluster formation is itself clustered. Interacting galaxies have been known for some time to host vast networks

of very massive star clusters whose formation is triggered by mergers or tidal interactions, e.g. the Antennae (Whitmore & Schweizer, 1995a) and M82 (de Grijs et al., 2001). However, as pointed out by Larsen & Richtler (1999) the formation of such cluster associations is not confined to merging galaxies. Dwarf galaxies (e.g. NGC 1569 and NGC 1705, O'Connell et al. (1994)) and undisturbed spiral galaxies (e.g. NGC 253, Watson et al. (1996), M101, Bresolin et al. (1996)) also exhibit very large star–forming complexes. Elmegreen & Elmegreen (1983) identified regularly–spaced strings of giant HII regions or HI clouds in the spiral arms of 22 galaxies, finding that individual concentrations of star–formation had typical size and mass scales of 1–4 kpc and 10^6–10^7 M$_\odot$ respectively, considerably larger than the sizes and masses of typical molecular clouds or OB associations.

Star–formation in the Milky Way itself also appears to occur on scales much larger than traditionally assumed. Shevchenko (1979) identifies more than ten indicators of star formation and lists 49 star–formation regions with masses of up to $\sim 10^6$ M$_\odot$. Efremov (1978) used Galactic Cephied variables to identify 35 complexes of star formation with sizes of ~ 600 pc and Barkhatova et al. (1989) used spatial and kinematic data on 69 open clusters to identify eleven star complexes with sizes ranging from $\sim 10^2$–$\sim 10^3$ pc. Efremov (1979) suggests that the sizes of these regions simply reflect the original sizes of the complexes of gas and dust from which they formed. He then proposes that the spatial and temporal distribution of star–formation within the complexes is a result of self–propagating star–formation driven by feedback from O–stars.

The study of star cluster complexes is therefore of great importance, since it will shed light on the importance of triggering in star formation on a variety of lengthscales. The evolution of such complexes is clearly an important factor in the formation and evolution of individual star clusters (Kroupa, 1998) and may also have a bearing on the origins of Ultra-Compact Dwarf galaxies and 'faint fuzzies' (Fellhauer & Kroupa, 2002a,b, 2005).

We propose the following MODEST questions:

- In the next year: Is star *cluster* formation itself always clustered, or do some clusters form and evolve alone?

- In the next three years: From an observational perspective, how do cluster complexes evolve and what is the role of triggering (on any scale) in their formation?

- In the next ten years: What bearing, if any, does the evolution of star cluster complexes have on the formation of the various dwarf-galaxy populations and the large faint star clusters (faint fuzzies)?

3 Globular Clusters

3.1 The production and evolution of blue stragglers

Blue stragglers are main-sequence stars which are more massive than the current turn-off mass. They have been seen in globular and open clusters, and in the halo. They are believed to form in two ways: either through collisions between lower-mass main-sequence stars (which will be relatively frequent in dense stellar clusters (Hills & Day, 1976)), or via mass transfer within binaries (Preston & Sneden, 2000; Piotto et al., 2004; Davies et al., 2004; Sandquist, 2005).

The subsequent evolution of merger and mass-transfer products remains an open question. Hydrodynamic calculations suggest that the collision remnants do not develop substantial convective regions during their thermal relaxation and therefore are not mixed significantly after the collision (Sills et al., 1997). If true, this would have a significant impact on the subsequent evolution of the

merger product, as the core would receive only a small amount of hydrogen and would, therefore, have a relatively short life. However, another key ingredient is the angular momentum contained in the merger product. Even a small, non-zero, impact parameter can result in an object with substantial angular momentum (Sills et al., 2002). This poses a problem for its subsequent evolution. The total angular momentum can be up to ten times larger than that possessed by low-mass pre-main-sequence stars. The collision product is expected to have quite a large radius soon after the merger and to then gradually contract back towards the main-sequence. However if no angular momentum were removed during the process, the object would reach the breakup velocity long before it reaches the main-sequence. Some mechanism must remove most ($\approx$99%) of the angular momentum. In pre-main-sequence stars angular momentum loss is driven by surface convection zones and magnetic winds, which are not expected to be present in collision products. Recently De Marco et al. (2004) inferred from spectroscopic data the existence of circumstellar discs around 6 stars in a sample of 50 objects located above the main-sequence in 4 globular clusters. The presence of magnetically locked discs had already been suggested as a possible mechanism to lose angular momentum (Leonard & Livio, 1995). The observed discs might not be massive enough to explain such an angular momentum sink, but they could be the leftovers of once larger discs.

Unfortunately very little observational data for BSS rotation rates in globular clusters currently exists. Only a few BSS in globular clusters have measured rotation so far (De Marco et al., 2005). Comparison between model predictions and observation can thus be made only on the basis of colour-magnitude diagrams. For example, Sills et al. (2005) claim that disc-free models of BSS are brighter and bluer than the objects observed so far and therefore imply that some angular momentum loss mechanism must be at work.

We propose the following MODEST tasks:

- In the next one to three years: spectroscopic observations of BSS will shed some light on the origin of BSS and on their subsequent evolution. Rotation rates, surface gravity and chemical abundances are fundamental information for probing collision models. Collisional BSS are expected to form at the centre of globular clusters. For this reason observing them spectroscopically will be quite challenging and will probably require instruments such as HST/STIS and ground-based adaptive-optic systems.

- In the next one to three years: improve models of rotating collisional products, and develop more detailed modelling of mass transfer in binaries. Predicted differences in the observables can help distinguishing collisional from primordial BSS.

3.2 Understanding the observed properties of extreme horizontal-branch stars

Extreme horizontal-branch (EHB) stars have been observed in several globular clusters as a group of objects considerably bluer than regular horizontal-branch stars. It is by now widely accepted that EHB stars are He burning stars that during their evolution have suffered heavy mass loss (Iben & Rood, 1970; Faulkner, 1972), keeping only a thin envelope (with mass of the order of 0.02 $M_\odot$). However the actual formation mechanism for such object is still unclear. Mass loss during the horizontal branch (HB) phase has been proposed (Wilson & Bowen, 1984; Yong et al., 2000), as well as enhanced mass loss rates during the previous red giant branch (RGB) phase (Soker et al., 2001), through several mechanisms. One of these involves binarity, i.e. tidal interactions within a close binary could enhance the envelope mass loss (Mengel et al., 1976; Heber et al., 2002; Han et al., 2002). However, preliminary results from spectroscopic data (Moni Bidin et al., 2006) show a lack of binaries among EHB stars in NGC 6752, in sharp contrast with the results of Peterson et al. (2002),

that concluded that the majority of EHB stars in this cluster are in binary systems. Apparently the two catalogues sample different regions in the cluster, the Peterson et al. (2002) one being located in more external regions. This could imply a different formation mechanism for EHB in the central and in the outer regions as has been observed for BSS in many clusters by looking at the luminosity functions (Ferraro et al., 2004). Recent results on the very massive clusters, ω Cen (Piotto et al., 2005) and NGC 2808 (D'Antona et al., 2005), indicate that the EHB stars in these two clusters could be the product of a second generation of stars formed by material enriched in He due to the pollution by SN and/or intermediate mass AGB stars. This would also explain the correlation found between the extension of the EHB and the mass of the clusters (Recio-Blanco et al., 1997).

We propose the following MODEST question and task:

- In the next one to three years: could dynamical interactions in dense stellar clusters trigger the large envelope mass loss believed to be at the orgin of EHBs?

- In the next one to three years: understand the binary distribution among EHB stars by observing other clusters.

3.3   Multiple episodes of star formation in some globular clusters?

Photometric studies of red giants in ω Cen have revealed several discrete populations covering the metallicity range $-1.5 \leq [\mathrm{M/H}] \leq -0.5$ with, possibly, an age spread of up to ~ 6 Gyr (Sollima et al., 2005). Additional observations have revealed the presence of a double main sequence, with a population of stars lying to the blue of the primary main sequence (Bedin et al., 2004). Spectroscopic follow-up measurements provided the surprising result that the blue main sequence is ~ 0.3 dex more *metal-rich* than the red population (Piotto et al., 2005), the most likely explanation being that the blue main sequence represents a super He-rich population of cluster members. This interpretation is interesting because ω Cen also possesses an EHB, for which one viable explanation is a population of He-rich stars.

A number of other globular clusters are also known to possess unusual stellar populations. Recent HST observations of NGC 2808 have demonstrated this cluster to also have a population of blue main sequence objects, although the main sequence does not show the clear bifurcation present in ω Cen (D'Antona et al., 2005). Again, this population has been interpreted as He-rich – a scenario which may also help explain NGC 2808's EHB. In addition, two Galactic bulge clusters (NGC 6388 and 6441) also possess EHBs despite their rather high metallicities ([Fe/H] ~ -0.5). Helium enhancement has been invoked to explain the anomalous HBs in these two objects. M54, which lies near the centre of the Sagittarius dSph galaxy, is suspected to possess a small metallicity spread (Da Costa & Armandroff, 1995), and has recently been shown to possess an EHB (Rosenberg et al., 2004). Finally, the very metal-poor remote halo cluster NGC 2419 also has an EHB. The one common property of these disparate clusters is that they are all among the most massive objects in the Galactic globular cluster system.

Both metallicity spreads and He-enhanced populations imply multiple episodes of star formation and self-enrichment in some globular clusters, likely involving Type II supernovae and/or winds from massive AGB stars. This picture is consistent with the observed correlation with mass, as only the most massive clusters are likely to be able to retain significant amounts of ejected gas. For example, the scenario proposed by D'Antona et al. (2005) to explain the NGC 2808 main sequence and EHB proposes three distinct episodes of star formation spread over several hundred Myr: the initial burst at big-bang He abundance ($Y \sim 0.24$), followed by a second generation with $Y \sim 0.4$ born from the winds of massive ($\sim 6-7 M_\odot$) first generation AGB stars, and later a third generation

with $Y \sim 0.26 - 0.29$ born from the winds of less massive ($\sim 3.5 - 4.5 M_\odot$) AGB stars. Similar scenarios have been proposed for ω Cen, although these often also include the possibility that this cluster was formerly the nucleus of a now-defunct dwarf galaxy. Numerous problems remain to be solved with self-enrichment models, involving, for example, the retention and mixing of ejected gas within a cluster, the required first-generation IMFs (to get enough AGB stars), and heavy-element pollution from Type II supernove.

We propose the following MODEST question and task:

- In the next one to three years: can material enrichment take place as a result of multiple mergers in very massive globular clusters?

- In the next three years: development of more comprehensive models of self-enrichment (including hydrodynamic modelling of accretion from interstellar gas within clusters) and multiple star-formation episodes within globular clusters.

3.4 Observing stars escaping from globular clusters

Measuring the properties of stars which are escaping from a particular globular cluster has the potential to tell us much about the internal processes in that cluster (eg, Gunn & Griffin, 1979). In particular, it would be of interest to try and find stars which have been ejected from the cluster with some significant velocity, as these offer a means of probing strong interactions between cluster members, such as three-body and four-body encounters (eg, Meylan et al, 1991). One possible way to locate such stars would be by measuring proper motions in a nearby target (e.g. M4) near the tidal radius or Lagrangian points. Once suitable candidates have been located, radial velocities could also be obtained. Because proper motion measurements require multi-epoch imaging over a significant baseline, this is necessarily a problem to be tackled on a time-scale of at least several years. Modelling can be utilized to predict the number of expected detections, and will be vital in attempting to constrain the processes which could produce the observed properties of any strong candidate high-velocity escapers. It is worth noting that for several Galactic globulars (e.g., Palomar 5, Odenkirchen et al, 2003; Leon et al, 2000), large numbers of escaped stars have been observed in the form of tidal tails. These are members which have drifted through the Lagrangian regions with small relative velocity, and are more useful for probing the cluster's orbit about the Galaxy as well as the Galactic mass distribution.

We propose the following MODEST questions:

- In the next three years: can we locate new tidal tails belonging to any Galactic globular clusters? Searches utilizing deep wide-field imaging are presently in progress.

- In the next three years: from a modelling aspect, can we predict the number of expected detections of fast escapers from a given globular cluster? Can we also constrain the processes which produce them, and predict their observational properties (e.g., the velocity distribution of fast escapers)?

- In the next ten years: can we locate high proper motion stars near the tidal boundaries of nearby globular clusters? If so, radial velocities of any candidate stars need to be obtained. What can the observed properties of such objects tell us about the internal processes in their parent clusters?

3.5 Observational constraints on binary star populations in globular clusters

Relatively little is known about binary star populations in globular clusters. Photometrically, we can begin to deduce probable binary candidates from the binary main sequence (eg, Rubenstein and Bailyn 1997). This is a region of the CMD lying above and to the red of the single-star main sequence. An unresolved binary consisting of two main sequence stars will have a combined colour somewhere in between the colours of the two components, and a magnitude brighter than that of the single-star main sequence at this combined colour. In principle, it is therefore possible to determine cluster binary fractions by observing the binary second sequence; however in practice this process is complicated by photometric errors, which mimic the main sequence spread due to binary stars, as well as crowding and field star contamination. Hence, to date binary fractions have only been measured at low significance in Galactic globular clusters via this method. Photometric variability surveys are also sensitive to some types of cluster binaries – in particular those which have the correct inclination to be eclipsing objects, plus those which are active in some manner, for example contact binaries (eg, Kaluzy et al. 1999). However, the relationship (if any exists) between active binaries and the global population is not known, so it is difficult, if not impossible, to infer properties of the normal binary population from the active one.

Cluster binaries can also be detected via spectroscopic observations (eg, Pryor et al 1989 ; Hut et al. 1992). The idea is to obtain radial velocity measurements at multiple epochs. Binary stars should show large variations in the measured radial velocity due to the orbital motions of the two components. Such measurements have the advantage that they can provide information about the orbital period, providing the sampling is suffiently frequent. The disadvantage of this technique is that it requires repeated time-consuming observations, and is rather inefficient considering the binary fraction is expected to be of order 10% or less.

A third way of probing a cluster's binary star population is by means of X-ray observations. With the launch of *Chandra* and *XMM–Newton*, many new X-ray sources have been detected in Galactic globular clusters. From all *ROSAT* observations, 57 X-ray sources were discovered in as many globular clusters (Verbunt 2001), but in 47 Tuc *Chandra* already found over 300 sources (Grindlay et al. 2001, Heinke et al. 2005). From *Chandra* observations of 12 globular clusters, Pooley et al. (2003) found that the number of X-ray sources with an X-ray luminosity above $4 \times 10^{30} \, \mathrm{erg \, s^{-1}}$ scales with the collision number. This scaling was interpreted as evidence that these X-ray sources, which are expected to be primarily cataclysmic variables, are formed through dynamical interactions. From the X-ray colours and luminosities it is possible to identify and classify the sources containing an accreting neutron star (a low-mass X-ray binary), but for the large part of the X-ray sources optical identifications are necessary to discriminate cataclysmic variables from magnetically active binaries (RS CVn, BY Dra, W UMa systems). Sofar, this has been done for 4 globular clusters; NGC 6752 (Pooley et al. 2002), 47 Tuc (Edmonds et al. 2003ab), NGC 6397 (Grindlay et al. 2001) and M4 (Bassa et al. 2004). These observations suggest that the majority of the X-ray sources with X-ray luminosities above a few times $10^{30} \, \mathrm{erg \, s^{-1}}$ are cataclysmic variables, while the fainter sources are active binaries. From a comparison of these identifications in M4, 47 Tuc and NGC 6397, it is found that the number of such active binaries appears to scale with the (core) mass of the cluster, instead of the collision number (Bassa et al. 2004). Hence it seems likely that these systems evolved from primordial systems.

We propose the following MODEST questions and tasks:

- In the next year: can we make any robust estimates of binary star fractions in globular clusters for which high-quality main sequence photometry already exists? This will require sophisticated statistical treatment of observational errors to disentangle the binary second

sequence. Does the spatial distribution of binaries look like what is predicted from dynamical models of star clusters (eg, Ivanova et al 2005)?

- In the next three years: the establishment of a detailed observing program of one nearby cluster (possibly M4), with the aim of determining the binary fraction, along with the distribution of mass ratios, periods, and separations for these objects. This will require both photometry and multiple-epoch spectroscopic measurements. In addition, can we start to establish a link between the active binary population in this cluster, and the overall population? This would allow us to start inferring the properties of binary populations in other clusters based on already-existing observations of the active systems.

- In the next ten years: if the M4-type measurements can be extended to several other clusters, we can start to build a global picture of binary populations in globulars, including intra-cluster variations. How do the characteristics of the binary populations vary with cluster properties (e.g., mass, concentration, etc)? What can this tell us about internal cluster dynamics?

3.6 Constraining initial conditions for globular cluster simulations

In recent years, star cluster simulations have reached new levels of power and sophistication. For example, we are now in a position to run direct collisional N-body models of objects at the lower end of the globular cluster mass function, incorporating much realistic physics (such as stellar and binary star evolution), for example see Hurley et al. 2005, where the open cluster M67 was modelled. With this type of modelling comes new challenges. One of the chief among these is the question of what initial conditions should be used for direct, realistic globular cluster simulations. Of course, the initial conditions adopted for any given run depend strongly on the system being modelled and the aims of the simulation. Nevertheless, it is important to develop a global understanding of how initial conditions affect subsequent evolution, in order that the *most suitable* starting point can be selected for any given simulation: can we constrain which initial conditions strongly affect subsequent long-term cluster evolution, and which are essentially irrelevant; or observationally, do we see any objects which will evolve into globular clusters like those in the Galaxy over the next Hubble time? Examples of modelling of globular clusters can be found in Phinney (1993), Druckier (1995), and Giersz & Heggie (2003).

There are two ways to address this problem. From a modelling point of view, as more and more large-scale simulations are calculated, with varying initial conditions, it should become clear which parts of parameter space (especially covering the IMF and initial spatial and velocity structures such as mass segregation) strongly influence cluster evolution, and how. Observationally, detailed measurements of very young star clusters can help provide constraints on realistic initial conditions. Such measurements have already been utilized in a number of studies – for example, the direct modelling of LMC clusters by (Mackey et al., 2006) involved initial conditions strongly constrained by the observed properties of young massive LMC objects such as R136, NGC 1805, and NGC 1818.

We propose the following MODEST questions:

- In the next year: begin to run simulations designed specifically to investigate the influence of initial conditions on the early, intermediate, and late-time evolution of globular clusters. Can we identify which are the most important initial conditions and which have little or no effect? Can we infer initial conditions from already-existing observations of young clusters?

- In the next three to ten years: Can one run direct or near-direct simulations with the aim of demonstrating whether the super star clusters observed in starburst and interacting galaxies

are really globular cluster progenitors? If they are not, then what did the Galactic globular clusters look like initially?

3.7 Are there black holes in globular clusters?

Low–mass black holes (LMBHs) are expected as the end products of the evolution of stars populating the uppermost end of the IMF – i.e., those with $M \geq 20M_\odot$. If such remnants are formed without significant initial velocity kicks, the retention fraction is expected to be high and the holes should constitute a dynamically important cluster sub-population (Kulkarni et al., 1993; Sigurdsson & Hernquist, 1993). Depending on the shape of the upper IMF, most if not all globular clusters are expected to possess this population of up to several hundred LMBHs early in their life. Within ~ 1 Gyr of formation, most LMBHs in a cluster have settled via mass segregation to form a centrally concentrated core. Eventually this core is sufficiently dense that multiple-hole interactions occur, resulting in the formation of BH-BH binaries and the ejection of single holes. Subsequent interactions harden the BH-BH binaries until eventually the recoil velocity is high enough for ejection. Several single holes are also expected to be ejected during this hardening process. Hence, it is thought that the LMBH population in a cluster completely depletes itself within a few Gyr. Nonetheless, the LMBH population is expected to inject significant amounts of energy into the stellar core in a cluster before depletion, both through the dynamical scattering of stars and the removal of BH mass from the cluster centre. N-body simulations show that this influence is in many cases enough to significantly alter (expand) the structure of the stellar core. Therefore, LMBHs likely represent an important (and often neglected) dynamical influence in the early and intermediate phases of star cluster evolution (Mackey et al., 2006).

Intermediate–mass black holes (IMBHs) in clusters are interesting because it is thought that such objects may represent the seeds of the super-massive black holes (SMBHs; $M > 10^6 M_\odot$) which are inferred to exist both in high-redshift galaxies (where they are believed responsible for quasars and AGN), and in the local universe at the centres of our Galaxy and M31. Stellar dynamical simulations suggest that IMBHs can be formed in very dense young globular clusters, via the process of *runaway merging*. In such clusters, the core-collapse timescale for the most massive stars can be shorter than their main sequence lifetimes. Core collapse may initiate a rapid sequence of direct collisions between stars, leading to the production of a merged object (possibly an IMBH) of mass $\sim 0.1\%$ of the cluster mass (Portegies Zwart & McMillan, 2002b). It is likely the inspiral and destruction of a suitable cluster near a galactic centre (e.g., the Arches or Quintuplet in our Galaxy) may seed or contribute to the growth of super-massive black holes ($M > 10^6 M_\odot$) as described in Section 4. The possibility of detecting IMBHs in globular clusters is thus both highly relevant and intriguing.

To date, we possess only indirect and/or debated evidence for IMBHs or populations of LMBHs in globular clusters. The presence of a $\sim 2500M_\odot$ IMBH in the nearby globular cluster M15 (Gerssen et al., 2002) and a $1.8 \times 10^4 M_\odot$ IMBH in the massive stellar cluster G1 in M31 (Gebhardt et al., 2005) have been inferred from HST measurements. However, these detections are contested by Baumgardt et al. (2003a,b), whose N-body modelling suggests that neither detection *requires* the presence of an IMBH – that is, each set of measurements can seemingly be explained by models with large central populations of stellar remnants such as neutron stars and white dwarfs. It has been suggested that detected X-ray emission from G1 may be the result of accretion of gas by a central black hole (Pooley & Rappaport, 2006). The more general question of which globular clusters may contain IMBHs has also been considered in Baumgardt et al (2005). The only evidence for LMBH populations in globular clusters is the observation (Mackey & Gilmore, 2003a,b) that intermediate age clusters in the Magellanic Clouds possess a wide range of core sizes, and that this

range apparently correlates with cluster age. This trend can, at least in part, be explained by the dynamical influence of LMBH populations (Mackey et al., 2006).

The main problem in detecting the presence of IMBHs (or centrally concentrated LMBH populations) in globular clusters is that these objects have only small spheres of dynamical influence: radius ~ 0.1 pc for a $2000M_\odot$ IMBH in a typical cluster core. At present therefore, measurements are limited by resolution. This problem will likely be solved on a time-scale of at least ten years, with the advent of $50-100$m-class telescopes and functional adaptive optics at visible wavelengths. Together these would permit full (3D) dynamical studies of globular clusters out to the Magellanic Clouds (Hook, 2005), allowing secure detections of IMBHs in globular cluster cores, as well as the possibility of investigating the effects of LMBH populations in intermediate-age clusters. In the meantime, ever more realistic modelling can help place constraints on both IMBH and LMBH formation in clusters, as well as what observational signatures should be expected from the presence of such objects.

We therefore propose the following MODEST questions:

- In the next year: using N-body modelling, can we make any new predictions about the observational signature(s) of a population of LMBHs in a globular cluster?

- In the next three years: can we resolve the disagreement between the observations of objects such as M15 and M31-G1 which infer the presence of IMBHs, and N-body modelling which suggests IMBHs are not required in order to explain the observed dynamics? Can we refine models of stellar evolution to make concrete predictions about whether we should really be expecting IMBHs or large populations of LMBHs in globular clusters?

4   Galactic nuclei

4.1   The final parsec problem

It is generally accepted that hierarchical models best explain the formation of structures in the Universe, down to the size of a galaxy (White & Rees, 1978; Kauffmann et al., 1993; Springel et al., 2005). This means that in their lifetimes galaxies typically merge with one or more other galaxies. A good example of this is the Antennæ "galaxy", which actually consists of *two* colliding galaxies, NGC 4038 and NGC 4039 (Whitmore & Schweizer, 1995b). Almost all galaxies appear to have a central supermassive black hole (SMBH, Ferrarese & Ford 2005 for a review), hence mergers of galaxies can eventually lead to mergers of the SMBHs (e.g., Menou et al., 2001; Haehnelt & Kauffmann, 2002; Volonteri et al., 2003). At the beginning of the evolution, dynamical friction makes the orbits of the SMBH decay, so that they sink down to the centre of the merging system. Strong interactions with surrounding stars coming from the stellar system in which the SMBHs are embedded remove energy and angular momentum from the SMBHs after they have formed a bound binary system. These stars are re-ejected into the stellar system with an increased kinetic energy and thus the semi-major axis of the SMBH binary shrinks. The rate of shrinking slows down after the SMBHs are close enough that they are more massive than the enclosed stellar mass. This typically happens at a separation $\sim 0.1-1$ pc, significantly larger than the $0.001-0.01$ pc needed so that gravitational radiation alone can cause the binary to merge within a Hubble time. The "final parsec problem" (Begelman et al., 1980; Milosavljević & Merritt, 2003; Yu, 2002) thus consists of identifying processes that can bring the binary separation from ~ 1 pc to the realm of significant gravitational radiation. The efficiency of such processes has major implications for the growth and mergers of SMBHs, galaxy evolution, and sources for future space-based

gravitational wave detectors such as the *Laser Interferometer Space Antenna* (*LISA*). For a comprehensive review of the various aspects of formation and evolution of binary MBHs we refer to Merritt & Milosavljević (2005).

In a galactic nucleus that has negligible amounts of gas and that has an axially symmetric potential, individual stars in the nucleus essentially conserve their angular momentum from orbit to orbit. Thus, after the stars whose pericentres take them near the SMBH binary are ejected from the system via a gravitational slingshot (hence the "loss cone" is emptied; see Frank & Rees 1976), further tightening of the binary requires that distant two-body encounters between stars send some of them on orbits radial enough to interact with the binary. The timescale for this two-body relaxation can be billions of years, but recent work based on the empirical relation between the mass of an SMBH and the velocity dispersion or mass of its host galaxy bulge (Ferrarese & Merritt, 2000; Gebhardt et al., 2000; Merritt & Ferrarese, 2001a,b; Tremaine et al., 2002) suggests that SMBH binaries with total mass $M_{\mathrm{BBH}} < 10^7 \, M_\odot$ can be hardened to merger in less than a Hubble time (Milosavljević & Merritt, 2003). This is the realm relevant to low-frequency gravitational wave detectors such as *LISA*. In contrast, it is still unclear whether a combination of other factors such as gas drag (Escala et al., 2005; Milosavljević & Phinney, 2005) or triaxiality of the galactic nuclear potential (Holley-Bockelmann et al., 2002; Poon & Merritt, 2002; Merritt & Poon, 2004) suffices to produce efficient mergers for more massive SMBH binaries.

Ideally, one would like to ensure inclusion of all relevant physical effects with a direct-summation N-body treatment of galactic centre dynamics. However, the actual number of stars in the central few parsecs of a galaxy is 10^{7-8}, which is too much to simulate in this way even for special-purpose supercomputers such as the GRAPE-6, which reach a computational power of 64 Tflops[1]. Using fewer particles decreases the effective two-body relaxation time and therefore introduces an artificially high rate of binary hardening.

A possible solution is parallel usage of a direct-summation N-body code on a cluster of special-purpose GRAPE-6 nodes. However at the present time, there is no N-body code which treats close encounters rigourously (through Kustaanheimo-Stiefel two-body as well as chain regularisation) and is both adapted for the use on GRAPE-6 and fully parallelized (Aarseth, 1999, 2003a).

Another possibility is that the real dynamics are not so sensitive to the number of stars. For example, it has been proposed that non-axisymmetries could help the binary shrink much faster thanks to the chaotic nature of the stellar orbits (Holley-Bockelmann et al., 2002; Poon & Merritt, 2002; Merritt & Poon, 2004). Recent work based on this approach suggests that the rate of orbital decay is roughly independent of the total number of particles (Holley-Bockelmann & Sigurdsson, 2006; Berczik et al., 2006). However, caution is appropriate because extrapolation to the much larger number of stars in real galaxies requires theoretical scalings which are not fully understood. N-body simulations should be therefore envisaged as a source of encouragement and motivation rather than solid and robust proofs.

For the MODEST questions on this subject we propose:

- In the next year: observationally, what is the dynamical state of a galactic centre just after a major merger? In particular, what is the rotational structure, and how triaxial are the centres?

- In the next three years: what is the influence of nuclear rotation on the dynamics of a SMBH binary? Initial investigations, e.g., Berczik et al. (2006), suggest that the influence could be substantial, but this needs to be coupled with observations.

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[1]`http://grape.astron.s.u-tokyo.ac.jp/grape/`

- In the next ten years: what is the evolution of the eccentricity of an SMBH binary from its formation until it becomes detectable with low-frequency gravitational radiation detectors such as *LISA*? This will require incorporation of rotation, triaxiality, and the effects of resonances on dynamical friction (Tremaine & Weinberg, 1984), and substantial input from analytical treatments, direct N-body summation techniques, and more approximate approaches. The potential payoff is that any residual eccentricity detected with *LISA* or similar instruments might then be used to untangle important elements of the mergers.

4.2 Stellar dynamics around a massive black hole

The central SMBH and the stellar system interact through many channels in addition to the smooth gravitational potential. For example, stars can produce gas to be accreted on to the SMBH, through normal stellar evolution, collisions, or disruptions of stars by the strong central tidal field. These processes may contribute significantly to the mass of the SMBH. Tidal disruptions trigger phases of bright accretion that may reveal the presence of an SMBH in an otherwise quiescent, possibly very distant, galaxy. Collisions may create observationally peculiar stellar populations. Also, stars too compact to be tidally disrupted are swallowed whole if they are kicked directly through the horizon ("direct plunges") or progressively inspiral down to a relativistic unstable orbit through emission of gravitational waves (GWs). The latter process, known as an "Extreme Mass Ratio Inspiral" (EMRI) will be one of the main targets of *LISA*.

Many different numerical schemes have been applied to the simulation of galactic nuclei hosting an SMBH. Most of them rely on the assumptions of an isolated, spherical system in dynamical equilibrium (e.g., direct integration of Fokker-Planck equation by Murphy et al. 1991, Monte-Carlo methods by Duncan & Shapiro 1982 and Freitag & Benz 2002, and gas-dynamical treatment by Amaro-Seoane et al. 2004). In these cases, only "collisional" effects can bring stars on to the loss-cone, i.e., the very elongated orbits which allow close interaction between a star and the SMBH. These effects include (diffusive) 2-body relaxation, large-angle scatterings, direct collisions, and resonant relaxation. The approximate methods just mentioned generally include only diffusive relaxation and, in rare cases, collisions and large-angle scatterings. There have only recently been direct N-body simulations of clusters with a central object (Baumgardt et al., 2004a,b; Preto et al., 2004, in particular).

As with binary SMBH simulations, for these applications N-body simulations are invaluable because they dispense with the necessity of most approximations but it seems unlikely that they will completely supersede other approaches in the next few years. Their most obvious limitation is the steep computing time scaling $t_{\mathrm{CPU}} \propto N_{\mathrm{part}}^{2-3}$ which currently limits the number of particles to about 10^6, short of the $10^7 - 10^8$ stars in even small galactic nuclei. More fundamentally, the community is missing an algorithm suitable to tackle this particular class of problems. The integration of millions of nearly Keplerian orbits with the Hermite scheme used in usual N-body codes causes spurious change in the orbital constants and may, for instance, lead to incorrect star-MBH interaction rates due to eccentricity increase. Therefore, numerical errors dominate the effects of the actual star-star perturbations.

The development of an N-body regularisation scheme to integrate the motion and mutual perturbations of a large number of light objects orbiting the same massive body has become a challenging priority. The chain scheme is not suitable here because it does not allow regularisation of the interaction of the SMBH with each close star simultaneously (see Aarseth 2003b for technical background). Some inspiration may be provided by the symplectic codes in use in planetary dynamics (Wisdom & Holman, 1991; Wisdom et al., 1996). These codes are optimised for nearly-Keplerian orbits with a single dominant object, and bound the energy error over large numbers of orbits.

They may therefore have applicability to the central regions of galactic nuclei that are dominated by an SMBH.

It is, however, likely that new development will be necessary for dynamics around an SMBH because excellent accuracy in all the orbital elements, not just the semimajor axis, may well be necessary to preserve the proper interactions with narrow resonances or to include the correct effects of processes such as general relativistic precession.

The inclusion of relativistic contributions to dynamics is especially important for the proper treatment of effects such as resonant relaxation (Rauch & Tremaine, 1996) or Kozai cycles (Kozai, 1962; Lidov & Ziglin, 1976; Innanen et al., 1997; Miller & Hamilton, 2002), which depend on the persistence of certain phase relations over hundreds of orbits or more. Even relatively small effects can have an influence over this many orbits, hence precision of integration and inclusion of relativity are at a premium. In addition, estimates of the distributions of mass ratio, eccentricity, etc., are needed to construct reliable template banks for detection of the gravitational radiation from EMRIs. Simulations based on purely Newtonian schemes may well lead to completely incorrect results for these purposes. General relativistic effects up to the 2.5 post-Newtonian order (and hence including both precession and radiation reaction) have been implemented in the codes HNBody (Gültekin et al., 2006) and N-body6++ (Kupi et al., 2006), but the applications are in their infancy.

Whatever the eventual solution, it is likely that such N-body codes will initially lack the efficiency to treat more than $10^4 - 10^5$ stars, corresponding to the inner part of the influence region of a realistic nucleus. An important first step would be to consider the central SMBH as a fixed particle, i.e., treat it as an external potential. Neglecting the random motion of the SMBH may have consequences for, e.g., the rate of tidal disruptions because this motion should allow loss-cone replenishment. However, this should only become an issue when a region larger than the influence radius can be simulated. Furthermore, this idealisation will prove useful for comparison with analytical and approximate numerical approaches which generally rely on it. It is also the best way to assess later the role of the SMBH motion by comparison with more realistic simulations.

To pave the way for N-body studies and to complement them, more approximate but much faster and more flexible methods are invaluable. Monte Carlo (MC) statistical approaches seem ideal because, being based on particles, they make it easier to follow the evolution of individual orbits and to include individual star-star or star-SMBH interactions. A promising avenue would be to combine aspects of the MC approach of Hopman & Alexander (2005, 2006) to that first pioneered by Hénon (1973) for globular cluster dynamics. Hopman & Alexander followed the orbital evolution of test particles due to diffusive and resonant relaxation and to GW emission in the Keplerian potential of the SMBH assuming a fixed stellar background. The Hénon approach would evolve the stellar distribution self-consistently –thus obtaining the correct mass-segregation effects– but its only application to galactic nuclei so far (Freitag & Benz, 2002) lacks the ability to resolve the dynamics of stars in or near the loss cone on satisfactorily short timescales. Shapiro and collaborators (Duncan & Shapiro, 1982; Shapiro, 1985) developed an MC code which represents the cluster as a set of spherical shells like in the Hénon scheme but where the effects of relaxation is computed by explicit integration of diffusion coefficients like in direct Fokker-Planck codes, rather than pairwise interactions between particles. This method had the important advantages of allowing one to increase the resolution in the central regions and to follow particles very close to the SMBH on orbital timescales, but it has only been used for single-mass cases. Such an algorithm, if it can be extended to a stellar mass spectrum, would be an extremely useful tool.

Theoretical predictions for rates and characteristics of EMRI events have proven quite problematic so far (see Sigurdsson 2003 for a quick review and Hopman & Alexander 2005, 2006 for new developments). Even in the standard case where only diffusive relaxation on single stars is considered, different authors find results scattered over such a large range that it is not clear whether

only a few events will be detected with *LISA* (Hopman & Alexander, 2005) or whether they will turn out to be an embarrassment of riches, preventing the individual detection of each other and of other sources (Barack & Cutler, 2004). Recently, non-standard processes to bring compact objects very close to an SMBH have been suggested. These include the accumulation of red-giant cores by tidal peeling (Davies & King, 2005), tidal separation of binaries (Miller et al., 2005), stellar formation in an accretion disk (Levin, 2003; Nayakshin, 2005) and dissipative interactions with a disk (Šubr et al., 2004). In all these cases, the orbital evolution will start being dominated by GW emission (as opposed to relaxation) at a smaller semimajor axis and much smaller eccentricity than in the "standard" case and the EMRI should be very nearly circular in the *LISA* band. The study of these various types of EMRIs will be one of the main applications of the numerical methods envisioned here.

Noticeably each of these processes was (also or uniquely) offered as a way to explain the origin of the young massive "S" stars orbiting Sgr A* (e.g., Genzel et al., 2003). Hence it is no coincidence that, unless they somehow get natal kicks comparable to their orbital speeds of thousands of kilometers per second, the remnants of the "S" stars will have the appropriate orbital parameters to become EMRIs, a fact with strong bearing on *LISA* detection rates if the situation around Sgr A* is typical.

It has also been suggested that intermediate-mass black holes (IMBH, with masses $\sim 10^{2-4}\,M_\odot$) formed in young massive star clusters within ~ 100 pc of the centre of a galaxy could sink to the centre and merge with an SMBH (Miller, 2005; Portegies Zwart et al., 2005; Matsubayashi et al., 2005). If this happens it would be an extremly strong source for *LISA*, with unique potential for mapping the spacetime around a rotating SMBH (Miller, 2005). Currently, however, there are many uncertainties about the various steps in the sinking process, from the settling of a cluster in a galactic nucleus to the stripping of that cluster to the processes that allow an IMBH to merge with an SMBH (for example, is there any stalling and if so, will other IMBHs come in and cause mutual ejection?).

Finally, while structures such as triaxial bulges, bars or stellar discs are common on scales of 100–1000 pc, the influence of non-sphericity at small and intermediate scales on the structure and evolution of the nucleus has been little explored. The existence of a large fraction of "centrophilic" (box and chaotic) orbits in triaxial structures has the potential of boosting the rate of star-SMBH interactions by orders of magnitude (Holley-Bockelmann et al., 2002; Poon & Merritt, 2002; Merritt & Poon, 2004; Holley-Bockelmann & Sigurdsson, 2006). For EMRIs, though, it is not clear whether such orbits, with very large initial semimajor axis and eccentricity, have a chance to shrink to *LISA*-detectable frequencies without being perturbed into a direct plunge or a wider orbit.

We therefore propose the following MODEST questions:

- In the next year: are the basic codes used to calculate EMRI rates consistent with each other? As proposed to us by Richard Mushotzky, we suggest that a precisely defined test case, accessible to direct N-body summation methods as well as to statistical approaches, should be simulated by several independent groups. Such comparison has proved very enlightening in the case of the "collaborative experiment" in cluster dynamics organised by Douglas Heggie (Heggie 2003, see also `http://www.manybody.org/modest/WG/wg7.html`) or in the field of cosmological hydrodynamics simulations (Frenk et al., 1999). For example, current codes could treat a cluster of 10^4 point-mass single stars hosting a central SMBH with a mass 1% of the total. Several quantities could be compared, including the time evolution of the capture rate. The observed similarities and differences could help guide further treatments. For the number of EMRIs to be significant with such a particle number, the cluster needs to

be made more compact than any known real system, to boost relativistic effects relative to relaxation. Although lacking physical realism, this setting will allow one to test and calibrate the approximate methods by comparison with direct N-body.

- In the next three years: what are the capture and tidal destruction rates implied by the actual distribution of stars around the SMBH in our own Galaxy? The radial dependence of number density is reasonably well constrained within ~ 0.01 pc of the centre, a region containing some 10^{4-5} stars, so a specific simulation over the $\sim 10^9$ yr relaxation time would be informative.

- In the next ten years: what is the true influence of nonaxisymmetry at large distances on the inner few parsecs, where EMRIs interact? Does this lead to large rates of *LISA* detections, or does it instead produce direct plunges? Before direct N-body methods are able to deal with $> 10^7$ particles, the relaxational dynamics of non-spherical systems could be studied with hybrid schemes borrowing from "collisionless" N-body and Fokker-Planck or MC codes, an option still virtually unexplored (with the exception of Johnston et al. 1999). As a separate but related matter, what are the processes that lead to an IMBH-SMBH merger, and what is the expected rate of *LISA* detections?

4.3 Stellar collisions

Galactic nuclei are one of the few environments in which collisions involving single stars should occur on a relatively short timescale. For instance, within ~ 0.03 pc of Sgr A*, a $1\,M_\odot$ main sequence (MS) star should experience, on average, one collision in less than 10 Gyr. For a giant, this timescale is reduced to a few 10^7 yr. Although collisions probably do not strongly influence the stellar dynamics, they are of great interest as a way to produce unusual stellar populations. They have been suggested as the cause of the apparent paucity of giants in the vicinity of Sgr A*, although giants irradiated by the X-ray radiation of Sgr A* may actually masquerade as massive MS stars (Jimenez et al., 2006).

Collisions in galactic nuclei occur at relative speeds of a few $100\,\mathrm{km\,s^{-1}}$ or higher, making mergers an unlikely outcome for low-mass stars. In particular the possibility of growing "super blue stragglers" through a sequence of collisions seems excluded. The mass and energy loss for such high-velocity collisions between MS stars has been studied exhaustively (Freitag & Benz, 2005) but much remains to be done for the more likely case of a collision between a giant and a more compact object. In relatively small galactic nuclei (typically hosting an SMBH less massive than $10^7\,M_\odot$), collisions involving stellar BHs are also of special importance because mass segregation probably concentrates these objects around the central SMBH (Freitag et al., 2006).

High-velocity collisions between a giant and a smaller star were computed, using SPH, by Bailey & Davies (1999) who found that during a typical collision the impactor, flying through the giant's envelope, causes only relatively little mass loss; the giant is likely to recover on a short (thermal) timescale. Complete removal of the envelope can only happen if the smaller star is captured and a common-envelope (CE) system is formed, an outcome too rare to explain the dearth of giants at the Galactic centre. On the other hand, Davies et al. (1998) showed that collisions between giants and binary stars may be more efficient at depleting the giant population, either by creating CE systems or by ejecting the giant's core from its envelope, if binaries are common enough. However, except for the detection of transient X-ray sources at < 1 pc from Sgr A* (Muno et al., 2005), very little is known about binary populations in galactic nuclei.

Our MODEST questions are:

- In the next year: what are the dynamics of binaries in galactic nuclei? The central goal is to study the survival of binaries in an environment with a much higher velocity dispersion than exists in globular clusters. It will be particularly important to study this question using stellar dynamical simulations with a large number of particles (see Sec. 4.2).

- In the next three years: what is the evolution and appearance of a giant star whose envelope has been partially removed by a collision (or a strong tidal interaction with the SMBH, see Di Stefano et al. 2001; Davies & King 2005). Also, what is the evolution of common envelope binaries formed through red giant collisions? These systems may be the progenitors of compact binaries, possibly explaining (some of) the X-ray sources observed around Sgr A*.

- In the next ten years: what are the hydrodynamic and possibly magnetohydrodynamic results of collisions between giants and smaller stars, and between compact objects (especially stellar-mass black holes) and extended stars? For the former, simulations need to cover a much more extended region of parameter space (masses, evolutionary stage of the giant, relative velocity and impact parameter) than published so far. For the latter, it will be important to understand how damaging the collisions are, and how much mass the compact star can accrete.

Acknowledgments

References

Aarseth S. J., 1999, PASP, 111, 1333

—, 2003a, Ap&SS, 285, 367

—, 2003b, Gravitational N-body Simulations. Tools and Algorithms. Cambridge University Press

Amaro-Seoane P., Freitag M., Spurzem R., 2004, MNRAS, 352, 655

Bailey V. C., Davies M. B., 1999, MNRAS, 308, 257

Barack L., Cutler C., 2004, Phys. Rev. D, 69, 082005

Barkhatova K. A., Osipkov L. P., Kutuzov S. A., 1989, Soviet Astronomy, 33, 596

Bassa C., Pooley D., Homer L., Verbunt F., Gaensler B. M., Lewin W. H. G., Anderson S. F., Margon B., Kaspi V. M., van der Klis M., 2004, ApJ, 609, 755

Baumgardt H., Hut P., Makino J., McMillan S., Portegies Zwart S., 2003a, ApJ, 582, L21

Baumgardt H., Makino J., Ebisuzaki T., 2004a, ApJ, 613, 1133

—, 2004b, ApJ, 613, 1143

Baumgardt H., Makino J., Hut P., 2005, ApJ, 620, 238

Baumgardt H., Makino J., Hut P., McMillan S., Portegies Zwart S., 2003b, ApJ, 589, L25

Bedin L. R., Piotto G., Anderson J., Cassisi S., King I. R., Momany Y., Carraro G., 2004, ApJ, 605, L125

Begelman M. C., Blandford R. D., Rees M. J., 1980, Nat, 287, 307

Berczik P., Merritt D., Spurzem R., Bischof H.-P., 2006, Efficient Merger of Binary Supermassive Black Holes in Non-Axisymmetric Galaxies. preprint, astro-ph/0601698

Bonnell I. A., Bate M. R., Clarke C. J., Pringle J. E., 1997, MNRAS, 285, 201

Bonnell I. A., Davies M. B., 1998, MNRAS, 295, 691

Bresolin F., Kennicutt Jr. R. C., Stetson P. B., 1996, AJ, 112, 1009

Clark P. C., Bonnell I. A., Zinnecker H., Bate M. R., 2005, MNRAS, 359, 809

Da Costa G. S., Armandroff T. E., 1995, AJ, 109, 2533

Dale J. E., Bonnell I. A., Clarke C. J., Bate M. R., 2005, MNRAS, 358, 291

D'Antona F., Bellazzini M., Caloi V., Pecci F. F., Galleti S., Rood R. T., 2005, ApJ, 631, 868

Davies M. B., Blackwell R., Bailey V. C., Sigurdsson S., 1998, MNRAS, 301, 745

Davies M. B., King A., 2005, ApJ Lett., 624, L25

Davies M. B., Piotto G., De Angeli F., 2004, MNRAS, 349, 129

de Grijs R., Gilmore G. F., Mackey A. D., Wilkinson M. I., Beaulieu S. F., Johnson R. A., Santiago B. X., 2002, MNRAS, 337, 597

de Grijs R., O'Connell R. W., Gallagher III J. S., 2001, AJ, 121, 768

De Marco O., Lanz T., Ouellette J. A., Zurek D., Shara M. M., 2004, ApJ, 606, L151

De Marco O., Shara M. M., Zurek D., Ouellette J. A., Lanz T., Saffer R. A., Sepinsky J. F., 2005, ApJ, 632, 894

Di Stefano R., Greiner J., Murray S., Garcia M., 2001, ApJ Lett., 551, L37

Drukier G. A., 1995, ApJS, 100, 347

Duncan M. J., Shapiro S. L., 1982, ApJ, 253, 921

Edmonds P. D., Gilliland R. L., Heinke C. O., Grindlay J. E., 2003a, ApJ, 596, 1177

—, 2003b, ApJ, 596, 1197

Efremov Y. N., 1978, Soviet Astronomy Letters, 4, 66

—, 1979, Soviet Astronomy Letters, 5, 12

Elmegreen B. G., 2000, ApJ, 530, 277

Elmegreen B. G., Elmegreen D. M., 1983, MNRAS, 203, 31

Escala A., Larson R. B., Coppi P. S., Mardones D., 2005, ApJ, 630, 152

Faulkner J., 1972, ApJ, 173, 401

Fellhauer M., Kroupa P., 2002a, MNRAS, 330, 642

—, 2002b, AJ, 124, 2006

—, 2005, ApJ, 630, 879

Ferrarese L., Ford H., 2005, Space Science Reviews, 116, 523

Ferrarese L., Merritt D., 2000, ApJ Lett., 539, L9

Ferraro F. R., Beccari G., Rood R. T., Bellazzini M., Sills A., Sabbi E., 2004, ApJ, 603, 127

Fleck J.-J., Boily C. M., Lançon A., Deiters S., 2006, MNRAS, 369, 1392

Frank J., Rees M. J., 1976, MNRAS, 176, 633

Freitag M., Amaro-Seoane P., Kalogera V., 2006, Stellar remnants in galactic nuclei: mass segregation. in preparation

Freitag M., Atakan Gürkan M., Rasio F. A., 2005, ArXiv Astrophysics e-prints

Freitag M., Benz W., 2002, A&A, 394, 345

—, 2005, MNRAS, 358, 1133

Frenk C. S., White S. D. M., Bode P., Bond J. R., Bryan G. L., Cen R., Couchman H. M. P., Evrard A. E., Gnedin N., Jenkins A., Khokhlov A. M., Klypin A., Navarro J. F., Norman M. L., Ostriker J. P., Owen J. M., Pearce F. R., Pen U.-L., Steinmetz M., Thomas P. A., Villumsen J. V., Wadsley J. W., Warren M. S., Xu G., Yepes G., 1999, ApJ, 525, 554

Gürkan M. A., Freitag M., Rasio F. A., 2004, ApJ, 604, 632

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., 2000, ApJ Lett., 539, L13

Gebhardt K., Rich R. M., Ho L. C., 2005, ApJ, 634, 1093

Genzel R., Schödel R., Ott T., Eisenhauer F., Hofmann R., Lehnert M., Eckart A., Alexander T., Sternberg A., Lenzen R., Clénet Y., Lacombe F., Rouan D., Renzini A., Tacconi-Garman L. E., 2003, ApJ, 594, 812

Gerssen J., van der Marel R. P., Gebhardt K., Guhathakurta P., Peterson R. C., Pryor C., 2002, AJ, 124, 3270

Geyer M. P., Burkert A., 2001, MNRAS, 323, 988

Giersz M., Heggie D. C., 2003, MNRAS, 339, 486

Goodwin S. P., 1997, MNRAS, 284, 785

Gouliermis D., Keller S. C., Kontizas M., Kontizas E., Bellas-Velidis I., 2004, A&A, 416, 137

Grindlay J. E., Heinke C., Edmonds P. D., Murray S. S., 2001a, Science, 292, 2290

Grindlay J. E., Heinke C. O., Edmonds P. D., Murray S. S., Cool A. M., 2001b, ApJ, 563, L53

Gültekin K., Miller M. C., Hamilton D. P., 2006, ApJ, 640, 156

Gunn J. E., Griffin R. F., 1979, AJ, 84, 752

Haehnelt M. G., Kauffmann G., 2002, MNRAS, 336, L61

Han Z., Podsiadlowski P., Maxted P. F. L., Marsh T. R., Ivanova N., 2002, MNRAS, 336, 449

Heber U., Moehler S., Napiwotzki R., Thejll P., Green E. M., 2002, A&A, 383, 938

Heggie D. C., 2003, in IAU Symposium, Makino J., Hut P., eds., p. 103

Heinke C. O., Grindlay J. E., Edmonds P. D., Cohn H. N., Lugger P. M., Camilo F., Bogdanov S., Freire P. C., 2005, ApJ, 625, 796

Hénon M., 1973, in Dynamical structure and evolution of stellar systems, Lectures of the 3rd Advanced Course of the Swiss Society for Astronomy and Astrophysics (SSAA), Martinet L., Mayor M., eds., pp. 183–260

Hills J. G., Day C. A., 1976, ApL, 17, 87

Holley-Bockelmann K., Mihos J. C., Sigurdsson S., Hernquist L., Norman C., 2002, ApJ, 567, 817

Holley-Bockelmann K., Sigurdsson S., 2006, A Full Loss Cone For Triaxial Galaxies. preprint, astro-ph/0601520

Hook I., 2005, The science case for the European Extremely Large Telescope : the next step in mankind's quest for the Universe. The science case for the European Extremely Large Telescope : the next step in mankind's quest for the Universe, Edited by I. Hook. Cambridge, UK: OPTICON and Garching bei Muenchen, Germany: European Southern Observatory (ESO), 2005

Hopman C., Alexander T., 2005, ApJ, 629, 362

—, 2006, Resonant relaxation near a massive black hole: the stellar distribution and gravitational wave sources. preprint, astro-ph/0601161

Hurley J. R., Pols O. R., Aarseth S. J., Tout C. A., 2005, MNRAS, 363, 293

Hut P., McMillan S., Goodman J., Mateo M., Phinney E. S., Pryor C., Richer H. B., Verbunt F., Weinberg M., 1992, PASP, 104, 981

Iben I. J., Rood R. T., 1970, ApJ, 161, 587

Innanen K. A., Zheng J. Q., Mikkola S., Valtonen M. J., 1997, AJ, 113, 1915

Ivanova N., Belczynski K., Fregeau J. M., Rasio F. A., 2005, MNRAS, 358, 572

Jimenez R., da Silva J. P., Oh S. P., Jorgensen U. G., Merritt D., 2006, Model Atmospheres for Irradiated Giant Stars: Implications for the Galactic Center. preprint, astro-ph/0601527

Johnston K. V., Sigurdsson S., Hernquist L., 1999, MNRAS, 302, 771

Kaluzny J., Thompson I., Krzeminski W., Pych W., 1999, A&A, 350, 469

Kauffmann G., White S. D. M., Guiderdoni B., 1993, MNRAS, 264, 201

Kozai Y., 1962, AJ, 67, 591

Kroupa P., 1998, MNRAS, 300, 200

—, 2004, New Astronomy Review, 48, 47

Kroupa P., Aarseth S., Hurley J., 2001, MNRAS, 321, 699

Kroupa P., Boily C. M., 2002, MNRAS, 336, 1188

Kulkarni S. R., Hut P., McMillan S., 1993, Nature, 364, 421

Kupi G., Amaro-Seoane P., Spurzem R., 2006, Dynamics of compact objects clusters: A post-Newtonian study. Submitted to MNRAS, preprint, astro-ph/0602125

Lada C. J., Lada E. A., 2003, ARA&A, 41, 57

Lada C. J., Margulis M., Dearborn D., 1984, ApJ, 285, 141

Larsen S. S., Richtler T., 1999, A&A, 345, 59

Leon S., Meylan G., Combes F., 2000, A&A, 359, 907

Leonard P. J. T., Livio M., 1995, ApJ, 447, L121+

Levin Y., 2003, Formation of massive stars and black holes in self-gravitating AGN discs, and gravitational waves in LISA band. astro-ph/0307084

Lidov M. L., Ziglin S. L., 1976, Celestial Mechanics, 13, 471

Mackey A. D., Gilmore G. F., 2003a, MNRAS, 338, 85

—, 2003b, MNRAS, 338, 120

Mackey A. D., Wilkinson M. W., Davies M. B., Gilmore G. F., 2006, in prep.

Maillard J. P., Paumard T., Stolovy S. R., Rigaut F., 2004, A&A, 423, 155

Matsubayashi T., Makino J., Ebisuzaki T., 2005, Evolution of Galactic Nuclei. I. orbital evolution of IMBH. ApJ, in press, astro-ph/0511782

McCrady N., Gilbert A. M., Graham J. R., 2003, ApJ, 596, 240

Mengel J. G., Norris J., Gross P. G., 1976, ApJ, 204, 488

Menou K., Haiman Z., Narayanan V. K., 2001, ApJ, 558, 535

Merritt D., Ferrarese L., 2001a, MNRAS, 320, L30

—, 2001b, ApJ, 547, 140

Merritt D., Milosavljević M., 2005, Living Reviews in Relativity, 8, 8

Merritt D., Poon M. Y., 2004, ApJ, 606, 788

Meylan G., Dubath P., Mayor M., 1991, ApJ, 383, 587

Miller M. C., 2005, ApJ, 618, 426

Miller M. C., Freitag M., Hamilton D. P., Lauburg V. M., 2005, ApJ Lett., 631, L117

Miller M. C., Hamilton D. P., 2002, ApJ, 576, 894

Milosavljević M., Merritt D., 2003, ApJ, 596, 860

Milosavljević M., Phinney E. S., 2005, ApJ Lett., 622, L93

Moni Bidin C., Moehler S., Piotto G., Recio-Blanco A., Momany Y., Mendez R. A., 2006, ArXiv
    Astrophysics e-prints (astro-ph/0602075)

Muno M. P., Pfahl E., Baganoff F. K., Brandt W. N., Ghez A., Lu J., Morris M. R., 2005, ApJ
    Lett., 622, L113

Murphy B. W., Cohn H. N., Durisen R. H., 1991, ApJ, 370, 60

Nayakshin S., 2005, Massive stars in sub-parsec rings around galactic centers. preprint,
    astro-ph/0512255

O'Connell R. W., Gallagher III J. S., Hunter D. A., 1994, ApJ, 433, 65

Odenkirchen M., Grebel E. K., Dehnen W., Rix H.-W., Yanny B., Newberg H. J., Rockosi C. M.,
    Martínez-Delgado D., Brinkmann J., Pier J. R., 2003, AJ, 126, 2385

Peterson R. C., Green E. M., Rood R. T., Crocker D. A., Kraft R. P., 2002, in ASP Conf. Ser. 265:
    Omega Centauri, A Unique Window into Astrophysics, pp. 255–+

Phinney E. S., 1993, in ASP Conf. Ser. 50: Structure and Dynamics of Globular Clusters, Djorgovski
    S. G., Meylan G., eds., pp. 141–+

Piotto G., De Angeli F., King I. R., Djorgovski S. G., Bono G., Cassisi S., Meylan G., Recio-Blanco
    A., Rich R. M., Davies M. B., 2004, ApJ, 604, L109

Piotto G., Villanova S., Bedin L. R., Gratton R., Cassisi S., Momany Y., Recio-Blanco A., Lucatello
    S., Anderson J., King I. R., Pietrinferni A., Carraro G., 2005, ApJ, 621, 777

Pooley D., Lewin W. H. G., Anderson S. F., Baumgardt H., Filippenko A. V., Gaensler B. M.,
    Homer L., Hut P., Kaspi V. M., Makino J., Margon B., McMillan S., Portegies Zwart S., van der
    Klis M., Verbunt F., 2003, ApJ, 591, L131

Pooley D., Lewin W. H. G., Homer L., Verbunt F., Anderson S. F., Gaensler B. M., Margon B., Miller J. M., Fox D. W., Kaspi V. M., van der Klis M., 2002, ApJ, 569, 405

Pooley D., Rappaport S., 2006, ApJ, 644, L45

Poon M. Y., Merritt D., 2002, ApJ Lett., 568, L89

Portegies Zwart S., Baumgardt H., McMillan S. L. W., Makino J., Hut P., Ebisuzaki T., 2005, The ecology of star clusters and intermediate mass black holes in the Galactic bulge. ApJ, in press, astro-ph/0511397

Portegies Zwart S. F., Baumgardt H., Hut P., Makino J., McMillan S. L. W., 2004, Nature, 428, 724

Portegies Zwart S. F., Makino J., McMillan S. L. W., Hut P., 1999, A&A, 348, 117

Portegies Zwart S. F., McMillan S. L. W., 2002a, ApJ, 576, 899

—, 2002b, ApJ, 576, 899

Preston G. W., Sneden C., 2000, AJ, 120, 1014

Preto M., Merritt D., Spurzem R., 2004, ApJ Lett., 613, L109

Pryor C., McClure R. D., Hesser J. E., Fletcher J. M., 1989, in Dynamics of Dense Stellar Systems, Merritt D., ed., pp. 175–181

Rauch K. P., Tremaine S., 1996, New Astronomy, 1, 149

Recio-Blanco A., Aparicio A., Piotto G., De Angeli F., Djorgovski S. G., 1997, å, accepted (astroph/0511704)

Rosenberg A., Recio-Blanco A., García-Marín M., 2004, ApJ, 603, 135

Rubenstein E. P., Bailyn C. D., 1997, ApJ, 474, 701

Sandquist E. L., 2005, ApJ, 635, L73

Schödel R., Eckart A., Iserlohe C., Genzel R., Ott T., 2005, ApJ, 625, L111

Shapiro S. L., 1985, in IAU Symp. 113: Dynamics of Star Clusters, Goodman J., Hut P., eds., pp. 373–412

Shevchenko V. S., 1979, Soviet Astronomy, 23, 163

Sigurdsson S., 2003, Classical and Quantum Gravity, 20, 45

Sigurdsson S., Hernquist L., 1993, Nature, 364, 423

Sills A., Adams T., Davies M. B., 2005, MNRAS, 358, 716

Sills A., Adams T., Davies M. B., Bate M. R., 2002, MNRAS, 332, 49

Sills A., Lombardi J. C., Bailyn C. D., Demarque P., Rasio F. A., Shapiro S. L., 1997, ApJ, 487, 290

Soker N., Catelan M., Rood R. T., Harpaz A., 2001, ApJ, 563, L69

Sollima A., Ferraro F. R., Pancino E., Bellazzini M., 2005, MNRAS, 357, 265

Springel V., White S. D. M., Jenkins A., Frenk C. S., Yoshida N., Gao L., Navarro J., Thacker R., Croton D., Helly J., Peacock J. A., Cole S., Thomas P., Couchman H., Evrard A., Colberg J., Pearce F., 2005, Nat, 435, 629

Tremaine S., 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., 2002, ApJ, 574, 740

Tremaine S., Weinberg M. D., 1984, MNRAS, 209, 729

Šubr L., Karas V., Huré J.-M., 2004, MNRAS, 354, 1177

Verbunt F., 2001, A&A, 368, 137

Vink J. S., de Koter A., Lamers H. J. G. L. M., 2001, A&A, 369, 574

Volonteri M., Haardt F., Madau P., 2003, ApJ, 582, 559

Watson A. M., Gallagher III J. S., Holtzman J. A., Hester J. J., Mould J. R., Ballester G. E., Burrows C. J., Casertano S., Clarke J. T., Crisp D., Evans R., Griffiths R. E., Hoessel J. G., Scowen P. A., Stapelfeldt K. R., Trauger J. T., Westphtptphal J. A., 1996, AJ, 112, 534

White S. D. M., Rees M. J., 1978, MNRAS, 183, 341

Whitmore B. C., Schweizer F., 1995a, AJ, 109, 960

—, 1995b, AJ, 109, 960

Wilson L. A., Bowen G. H., 1984, Nature, 312, 429

Wisdom J., Holman M., 1991, AJ, 102, 1528

Wisdom J., Holman M., Touma J., 1996, Fields Institute Communications, Vol. 10, p. 217, 10, 217

Yong H., Demarque P., Yi S., 2000, ApJ, 539, 928

Yu Q., 2002, MNRAS, 331, 935