MODEST-2: a summary

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Abstract

This is a summary paper of MODEST-2, a workshop held at the Astronomical Institute 'Anton Pannekoek' in Amsterdam, 16–17 December 2002. MODEST is a loose collaboration of people interested in MOdelling DEnse STellar systems, particularly those interested in modelling these systems using all the available physics (stellar dynamics, stellar evolution, hydrodynamics and the interplay between the three) by defining interfaces between different codes. In this paper, we summarize: (1) the main advances in this endeavour since MODEST-1; (2) the main science goals which can be and should be addressed by these types of simulations; and (3) the most pressing theoretical and modelling advances that we identified.
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1. Introduction

Dense stellar systems can roughly be defined as environments in which the interactions between individual stars play a crucial role. At the very least, two-body relaxation is short enough to have changed the stellar distribution function significantly since the formation of the system; and in the more interesting cases, actual stellar collisions have changed the properties of individual stars. These two effects are related: relaxation can lead to the dynamical segregation of binaries in the core, increasing the rate of encounters and the temporary capture of single stars or members of other binary stars, providing episodes that enhance the probability of physical collisions between stars.

Our observational insight into dense stellar systems has advanced enormously during the last decade. The Hubble and Chandra telescopes have allowed us to peer into the dynamical heart of the densest globular clusters, we have found stars orbiting the central black hole in our galaxy, and infrared observations have penetrated into the most obscured areas of star forming regions, where protostars can physically interact with each other before settling down as relatively more isolated stars.

From a theoretical point of view, the challenge has long been to model the ecological network of interactions coupling the stellar evolution and stellar dynamics of dense stellar systems. While the 1980s saw more and more detailed dynamical models of globular clusters, it was only in the later '90s that these models started to incorporate some approximate form of stellar evolution, based on fitting formulae, and binary star evolution, based on recipes. The next step will be to model the merging process of colliding stars more accurately, and to incorporate more detailed forms of on-the-fly modelling of the stellar evolution of the dynamical merger products.

Simulations of dense stellar systems currently face two major hurdles, one astrophysical and one computational. The astrophysical problem lies in the fact that several major stages in binary evolution, such as common envelope evolution, are still poorly understood. The best we can do in these cases is to parameterize our ignorance, in a way that is reminiscent of the introduction of a mixing length to describe convection in a single star, or an alpha parameter in modelling an accretion disk. The hope is that by modelling a whole star cluster in great detail, and comparing the results to the wealth of observational data currently available, we will be able to constrain the parameters that capture the unknown physics.

There is an interesting parallel with the way single stars were modeled, notwithstanding the fact that there were uncertainties in various aspects of its microscopic physics. An early triumph of stellar evolution was the prediction of an excited state in the ^{12}C nucleus, in order to reconcile the results of stellar evolution calculations with observations, a prediction that soon afterward was confirmed in the laboratory. And more recently, neutrino mixing has been confirmed as the explanation for a long-standing discrepancy between the standard model for the evolution of the Sun and direct observations of the neutrino flux coming from the core of the Sun.

Our hope is that the more complex modelling of whole star clusters will similarly shed light on the 'microphysics' input, in this case the poorly known fate of complex stages of binary star evolution. But in order to constrain scenarios for common envelope evolution, for the formation of millisecond pulsar binaries, etc., we need to construct accurate models for the evolution of dense stellar systems. This brings us to the second major hurdle, which is of a computational nature. The problem is one of composition: while we have accurate computer codes for modelling stellar dynamics, stellar hydrodynamics, and stellar evolution, we currently have no good way to put all this knowledge together in a single software environment.

It was the goal of the MODEST-1 meeting, in New York City in the summer of 2002, to begin addressing this problem. The MODEST acronym was coined during this meeting, and it can stand not only for MOdelling DEnse STellar systems, but also for MODifying Existing STellar codes. The latter description stresses the desirability to start with what is already available, and to find ways to put it all together, rather than to try to write a kitchen-sink type over-arching super code from scratch. We refer to the MODEST-1 review paper for further background (Hut et al., 2003), and also to the MODEST website: http://www.manybody.org/modest.html.

The present paper offers a summary of the presentations and discussions held during the MODEST-2 workshop, organized at the University of Amsterdam, Holland, by Simon Portegies Zwart and Piet Hut, in December 2002. This paper contains the input of many participants, who are listed below under the acknowledgments. While many of the authors have contributed to various sections, each section has main author(s), as follows. Section 1 was written by Piet Hut, Section 2 was written by Marc Freitag, Mirek Giersz, Stefan Deiters, Natasha Ivanova, James Lombardi and Steve McMillan, Section 3 was written by Ralf Klessen, Pavel Kroupa and Hans Zinnecker, Section 4 was written by Steve McMillan, Jarrod Hurley, Peter Eggleton, Simon Portegies Zwart and Alison Sills, Section 5 was written by Douglas Heggie, and Sections 6 and 7 were written by Alison Sills.

MODEST-2 was an informal workshop, consisting of 8 short talks from participants outlining how their work fits into the MODEST framework, what they want to get out of participation in MODEST, what the most relevant questions are for their area, or what they have accomplished since MODEST-1. There was also a fair amount of time allocated for general discussion of science goals and short-term theoretical goals before the next MODEST meeting. Finally, we spent some time discussing the long-term goals and best way to future of the collaboration.

The biggest difference between MODEST-1 and MODEST-2 was a concentration on WHAT rather than HOW. MODEST-1 was spent deciding that the different communities (evolution, dynamics, hydrodynamics) could and should work together, and then discussing exactly how they wanted to do that—the details of the interface. At MODEST-2, we spent some time discussing the interfaces and their implementation (see Section 2.4) but most of the time was spent talking about the different scientific issues that the MODEST collaborators wanted to see addressed. This paper attempts to capture the tone of the meeting, and outline the current state of MODEST research.

2. Progress since MODEST-1

MODEST-2 was held 6 months after MODEST-1.

In that time, some advances were made on combining stellar evolution, stellar dynamics and hydrodynamics in modelling dense star clusters. In addition, some groups have made progress in other areas of cluster modelling that are relevant to the MODEST collaboration. In this section we summarize the recent work on both these fronts. In Section 2.1, Marc Freitag and Natasha Ivanova discuss Monte Carlo codes that include the effects of stellar collisions. In Section 2.2, Mirek Giersz discuses the alternatives of using scattering cross sections and 'live' few-body integrations in hybrid codes. Stefan Deiters describes the gaseous codes in Section 2.3. And in Section 2.4, Jamie Lombardi, Steve McMillan and Jarrod Hurley discuss their implementation of the MODEST-1 interface between stellar dynamics, hydrodynamics and stellar evolution.

2.1. Monte Carlo cluster simulations with stellar collisions

2.1.1. A Monte Carlo code for galactic nuclei simulations

In the past few years, a new Monte Carlo (MC) code has been developed to follow the long term evolution of galactic nuclei (Freitag and Benz, 2001, 2002b; Freitag, 2001). This tool is based on the scheme first proposed by Hénon (1973) to simulate globular clusters but, in addition to relaxation, it also includes collisions, tidal disruptions by a central massive black hole (BH), stellar evolution and captures of stars by a central BH through emission of gravitational waves.

The MC technique assumes that the cluster is spherically symmetric and represents it as a set of particles, each of which may be considered as a homogeneous spherical shell of stars sharing the same orbital and stellar properties. The number of particles may be lower than the number of stars in the simulated cluster but the number of stars per particle has to be the same for each particle. Another important assumption is that the system is always in dynamical equilibrium so that orbital time scales need not be resolved and the natural time-step is a fraction of the relaxation (or collision) time. The relaxation is treated as a diffusive process (Binney and Tremaine, 1987).

Contrary to methods based on an integration of the

Fokker–Planck (FP) equation, with which it shares most assumptions, the particle-based MC approach allows for a more direct inclusion of further physics, like collisions, tidal disruptions, captures, large-angle scatterings or interaction with binaries. Other advantages over the FP codes include the fact that the MC scheme handles a continuous stellar mass spectrum and an arbitrary (anisotropic) velocity distribution without added difficulty. Thank to a binary tree structure that allows quick determination and update of the potential created by the particles, the self gravity of the stellar cluster is accurately accounted for.

The CPU time required by direct N-body simulations scales with the number of particles N like N^{2-3}, thus imposing a limit on N of order a few 100 000, even with special-purpose GRAPE computers. In contrast to this, MC runs, whose CPU time scales like $N \ln(N)$, routinely use 500 000 to a few millions of particles on run-of-the-mill PCs. Such high numbers of particles mean that, for the first time, globular clusters can actually be modelled on a star by star basis (Giersz, 1998, 2001; Joshi et al., 2000, 2001; Watters et al., 2000).

2.1.2. Including stellar collisions

Collisions between main sequence (MS) stars are treated with a high degree of realism through the use of a comprehensive set of $\sim 15\,000$ SPH (Smoothed Particle Hydrodynamics, Benz, 1990) simulations (Freitag, 2000; Freitag and Benz, 2002a, 2003). Reducing this huge amount of data into a set of fitting formulae giving the outcome of a stellar solution as a function of its initial conditions (the masses of the stars, the relative velocity and the impact parameter) has so far proven inconclusive. Thus, an interpolation scheme was used, based on a Delaunay tessellation of the 4D, irregularly populated initial parameter space to produce a 4-index lookup table. Interestingly, it appears that the collisional mass loss, as determined by SPH simulations is quite precisely predicted by a very simple semi-analytical model of collisions, first proposed by Spitzer and Saslaw (1966), that considers only conservation of momentum and total energy, as soon as the relative velocity at infinity is higher than the escape velocity from the surface of a star and the impact parameter is larger than about $0.5(R_1 + R_2)$ where $R_{1,2}$ are the stellar radii. This regime is mostly relevant to collisions in a galactic nucleus, near the central BH. This raises hope that some quick semi-analytical way of treating high-velocity collisions can be devised that would complement the work done Lombardi and his collaborators for parabolic encounters (Lombardi et al., 2002). Of particular interest would be the development of some entropy-sorting algorithm to determine the post-collisional stellar structure. This information is indeed required to compute the subsequent evolution of stars that have suffered from collisions. Unfortunately, it is doubtful that it can be extracted from Freitag's SPH simulations that are of relatively low resolution and make use of unequal mass particles, two facts that may lead to important spurious mixing according to Lombardi et al. (1999).

As shown independently by Rasio (1991) and Hernquist (1993), the usual formulations of SPH that use variable smoothing lengths fail to conserve energy and entropy simultaneously. However, Springel and Hernquist (2002) have recently derived SPH equations of motion that, by construction, conserve both energy and entropy even when the smoothing is adaptive. The derivation utilizes a Lagrangian, with Lagrange undetermined multipliers employed to satisfy the constraint that the total mass within the smoothing volume of each particle be held constant. Although the corrections introduced by this new method become vanishingly small as the number of particles $N \rightarrow \infty$, it does seem to be a fundamentally better formulation of SPH. Live (that is, on-the-fly) SPH calculations in a cluster simulation, for example, could benefit significantly from such a method, as they could achieve higher accuracy for a fixed (and presumably relatively small) number of particles.

In the simulations of Freitag (2000), either of two very simple assumptions were used to set the stellar evolution of mergers. *(1) Complete rejuvenation.* The merger is assumed to be completely mixed during the collision and is put back on the zero-age MS. This is quite unphysical and obviously leads to an important overestimate of the merger's MS lifetime but corresponds to the assumption made in many previous works (Quinlan and Shapiro, 1990, for instance). *(2) Minimal rejuvenation.* In this case, during a coalescence, the helium cores of both parent stars merge together, while the hydrogen envelopes combine to form the new envelope; no hydrogen is

brought to the core. An effective age is assigned to the merger by using a linear relation for the mass of the helium core as a function of the time spent on the MS and resorting to 'normal' stellar evolution models to provide the mass of the helium core at the end of the MS (Hurley et al., 2000; Belczynski et al., 2002). In both cases, if the stars don't merge no rejuvenation is assumed. Also, the thermal time scale is always assumed to be much shorter than the average time between collisions so that the MS mass–radius relation is applied to collisions products.

2.1.3. A route to intermediate mass black holes

Many scenarios have been proposed for the formation of massive BHs in the center of dense stellar clusters (Begelman and Rees, 1978); most of them require further investigation. Here, we explore the growth of a very massive MS star (a few $\times 10^2$ to $\sim 10^4\,M_\odot$) by run-away merging of stars (Rasio and Freitag, 2003). If its metallicity is sufficiently low, such an object is likely to form an intermediate mass BH (IMBH, with $M_{BH} \simeq 100 - 10^4\,M_\odot$) at the end of its life (Fryer and Kalogera, 2001; Woosley et al., 2002). This run-away route has been shown to operate in FP models of simple proto-galactic nucleus models by Quinlan and Shapiro (1990), hereafter QS90) and in *N*-body simulations of populous young clusters by Portegies Zwart and McMillan (2002). In the later case, stellar collisions occur in dynamically formed binaries and the authors argue that the condition for run-away to occur is that the time scale for the most massive stars ($M_* \simeq 100\,M_\odot$) to segregate to the center of the cluster, T_{segr}, be shorter than their MS life-time, of order 3 Myrs. Freitag's MC code cannot account for binaries. This is not a serious concern because their formation and survival in high-velocity galactic nuclei is unlikely. As the stellar density rises to higher and higher values during the (segregation-driven) core collapse, collisions are bound to occur even without the mediation of binaries.

For definiteness, we concentrate here on QS90's model E4A, a Plummer cluster with initial central values of the density and of the 3D velocity dispersion of $3 \times 10^8\,M_\odot\,pc^{-3}$ and $400\,km\,s^{-1}$. QS90 started their FP simulations with all stars having $1\,M_\odot$ and assumed that all collisions lead to mergers and that complete rejuvenation is valid. Not surpris-

ingly, if we use the same, unrealistic, treatment of collisions as QS90, we get clear run-away growth of one or a few particles. When we switch to the realistic SPH prescription for the collisions and minimal rejuvenation, we still get run-away. However, if we initiate the cluster with a more realistic extended IMF (Kroupa, 2001), important mass loss from the massive stars occurs before core collapse has proceeded to high stellar densities. As we assume that the gas is not retained in the cluster, this mass loss drives the re-expansion of the whole system. A second, deeper core collapse occurs later, when the stellar black holes segregate to the center. The subsequent evolution of this dense cluster of stellar BHs cannot be treated with Freitag's MC code because dynamically formed binaries will play a central role. Whether an IMBH may grow in such an environment is a debated issue (Portegies Zwart and McMillan, 2000; Miller and Hamilton, 2002).

In addition to models with the same densities and velocity dispersions as considered by QS90, Freitag also simulated clusters with densities 3 and 9 times larger with correspondingly shorter relaxation times and, hence T_{segr}. Run-away growth happens in all simulations with $T_{segr} < 3\,Myrs$ but in none of the other cases. The growth of the run-away particle(s) is limited to a few $100\,M_\odot$ ($650\,M_\odot$ in the 'best' case), probably by some still unelucidated numerical artifact. Note that 500 000 particles were used for these computations, independently of the number of stars to simulate. Hence, every particle represents many stars (12 to 36 for the simulations discussed here), a numerical treatment whose validity becomes obviously questionable as soon as a single particle detaches from the overall mass spectrum. Anyway, before the run-away particle abruptly stops accumulating mass, its growth is extremely steep. Once started, it occurs on a time scale much shorter than stellar evolution and it seems that it can only be terminated by some instability setting in in the structure of the massive star, the inefficiency of collisional merging[1], the depletion of the 'loss-cone' orbits that bring stars to the center or some combina-

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[1] Freitag has not computed SPH collision simulations for stars more massive than $75\,M_\odot$ so considerable extrapolation of the results is required.

tion of these factors. Despite these uncertainties, stating that run-away merging produces stars at least as massive as $500\,M_\odot$ in the center of clusters with $T_{segr} < 3$ Myrs is a robust conclusion.

2.1.4. Monte Carlo codes for globular cluster evolution

The Monte Carlo code StarFokker, being developed by A. Gürkan and F. Rasio at Northwestern and J. Fregeau at MIT (see Joshi et al., 2000, 2001; Fregeau et al., 2002; Watters et al., 2000), currently has the following features: fast integration of large numbers of stars (up to 4×10^6 stars for a Hubble time in about a week of computing time), tidal truncation of the cluster, simple treatment of stellar collisions (sticky sphere approximation), binary–binary interactions with simple recipes (based on the previous Fokker–Planck study by Gao et al., 1991), binary–single interactions with direct integration (using scatter3 from STARLAB) and single star evolution (based on Hurley et al., 2001). Work is in progress to incorporate a new 4-body integrator (developed by J. Fregeau) for binary–binary interactions, as well as a full treatment of binary star evolution based on the population synthesis code StarTrack (developed by K. Belczynski and V. Kalogera at Northwestern; Belczynski et al., 2002). A new study of equal-mass clusters with primordial binaries was recently completed (Fregeau et al., 2003), showing that, in an isolated cluster, primordial binary burning can easily support the cluster against core collapse for many Hubble times as long as the initial binary fraction is larger than a few percent. After the initial core collapse, gravothermal oscillations powered by the remaining primordial binaries are always observed. The Monte Carlo simulations also show the temperature inversion in the core expected during re-expansion (Makino, 1996; Giersz, 1998). In tidally truncated clusters with primordial binaries, the models suggest that complete disruption of the cluster often happens before core collapse. Comparisons between the simple recipes and direct dynamical integrations for 3-body (binary–single) interactions show that the recipes are reasonably accurate. However, binary–binary interactions are dominant for the evolution of most cluster models with initial binary fractions above a few percent.

A new Monte Carlo code, IMGE, that incorporates

a lot of the new ideas discussed at the MODEST-1 workshop, is being developed by A. Gürkan at Northwestern. Initial conditions are handled as in STARLAB, and the code uses the FITS format to store snapshots that can be read back in. Currently, this code can only treat the evolution of an isolated cluster of single stars.

2.2. Hybrid code—cross sections for three- and four-body interactions

Spherically symmetric equal mass star clusters containing a large amount of primordial binaries are studied using a hybrid method, consisting of a gas dynamical model for single stars and a Monte Carlo treatment for the relaxation of binaries and three- and four-body encounters. The initial conditions are as follows: a cluster of 300 000 single stars and 30 000 binaries, both distributed in Plummer's model density distribution with a constant density ratio between binaries and single stars. All binaries are set up with a so-called thermal eccentricity distribution, and binding energies are equally logarithmically distributed between 3 and 400 KT. Each binary–single star/binary encounter is investigated by means of a highly accurate direct few-body integrator (kindly supplied by S.J. Aarseth with his NBODY6 program package). Hence, hybrid codes can study the systematic evolution of individual binary orbital parameters and differential and total cross sections for hardening, dissolution or merging of binaries from a sampling of several ten thousands of scattering events as they occur in real cluster evolution (see Giersz and Spurzem, 2003, for details).

For three-body encounters Giersz and Spurzem find a good agreement of the nearly entire differential cross section with Spitzer's (1987) expression, except for very small energy changes. This is not surprising, because of the limited coverage of phase space for all encounters with small energy changes in real cluster models compared to artificial experiments. The formation of bound three-body subsystems and binary dissolutions are not very probable. Merging (interactions with minimum distance smaller than 1 $R_\odot$), as expected, occurs preferentially at high Δ (relative binary binding energy change). For smaller Δ non-merging encounters dominate.

For four-body encounters, the hybrid code results

are in good agreement with Spitzer's (1987) and Heggie's (1975) analytical formulae for $\Delta > 0.1$. For smaller Δ, as it was predicted by Heggie's (1975) analytical work for a tidal, adiabatic encounter the differential cross section is proportional to $1/(\Delta)$ $\log(\Delta)^{1/3}$. For strong encounters hardening of one binary and dissociation of another dominates. For $\Delta < 1$ there is a competition between dissociation and stable end configurations (resulting in two surviving binaries). At small energy changes formation of bound quadruples and stable hierarchical triples is the most probable reaction channel. It is interesting to note that Spitzer's and Heggie's formulae for three-body interactions also describe with good accuracy four-body interactions.

For the first time, our study gives a complete overview of the behavior of eccentricities in binaries embedded in an evolving star cluster. We also find a new approximate law to fit our empirical cross sections for eccentricity changes. The effects of flybys and close encounters can be clearly distinguished. For the three-body encounters, for initially nearly circular orbits, all final eccentricities after a three-body encounter occur with equal probability. If there is already some initial eccentricity the probability to reach any higher eccentricity is approximately constant, while the chance to go back to a less eccentric orbit decays exponentially ($\propto \exp(4e_{init})$). This is even more pronounced for initially highly eccentric binaries. For the four-body encounters a bimodal distribution of final eccentricities, depending on whether we look at strong encounters or at weak ones, can be seen. For strong encounters, the initial eccentricity is 'forgotten' in the sense that all differential cross sections have a maximum at high final eccentricities and decay again with the characteristic law seen already in three-body encounters. For weak encounters (fly-bys) there is no strong interaction and hence no strong eccentricity change. Finally, it is interesting to note that in all evolutionary stages a so-called thermal eccentricity distribution is maintained at all binary binding energies.

2.3. Gaseous models

The gap between direct models and the most interesting particle numbers in real globular star clusters can until now only be bridged by theory.

The gaseous model (Louis and Spurzem, 1991, http://www.gaseous-model.de) for example makes use of the remarkable resemblance between a star cluster containing a large number of stars and a self-gravitating gaseous sphere with a huge number of atoms (a generalization to axisymmetric systems has not yet been tackled). Its model equations are obtained as a set of moment equations of the local Fokker–Planck equation. Compared to direct solutions of the orbit-averaged Fokker–Planck equations, it is easier to add new physics and faster standard numerical solvers can be used (see for a comparison e.g. Giersz and Spurzem, 1994).

The gaseous model played an important role in theory, but up to now it has not been used to model observations directly. Concepts of gravothermal contraction and oscillations (Lynden-Bell and Eggleton, 1980; Bettwieser and Sugimoto, 1984) have been derived in the context of gaseous models and have proven to be very useful even now in the time of huge direct *N*-body modelling. Comparisons between the different models have produced promising results, so the time has come to improve the gaseous model in order to get a more realistic model that is capable of modelling real star cluster observations. In a first step the effects of stellar evolution in the model were included using the stellar evolution routines of Hurley et al. (2000) and generated artificial color-magnitude diagrams. Although these diagrams cannot be compared with observed ones, one gets a first idea of the strength of the model: For example one can observe how population gradients develop (heavy remnants sink to the center and low mass stars migrate to the outskirts). More features need to be included, among them kicks of neutron stars, a tidal field, dynamically active binaries, collisional cross sections and binary star evolution in the code. This would make the gaseous model a powerful tool to model observations of globular star clusters. It could be also used to conduct huge parameter studies in order to find a set of initial parameters for higher precision models (Deiters et al., 2003).

2.4. The stellar dynamics–stellar evolution–hydrodynamics interface

One of the goals of the MODEST-1 workshop was to specify ways to let existing computer codes for

stellar dynamics (SD), stellar evolution (SE) and stellar hydrodynamics (SH) communicate with minimum modification. With a well-defined minimal interface, each of the three modules should see the others as a black box. For example, the SD module should not care whether the SE data result from running a live SE code, or from a look-up table or fitting formula.

Immediately following the first workshop, Hut and Makino wrote a toy model version for the SD–SE interface. In order to test their interface, they constructed a very simple implementation of both the SD and SE parts of a simulation code. For the SD they envisioned two unbound stars on a head-on collision course that merge into a single star with an unusual composition. If mass loss during the collision is neglected, and if the collision product is approximated as fully mixed, then the SH module is effectively bypassed. Their SE code then approximates the stellar mass, radius and chemical compositions of the collision product with a piece-wise linear function in time, with one discontinuity. A more detailed description of their SE module, as well as the source code in both Fortran and C++, is publicly available online[2].

The intent of Hut and Makino is that their code would be the instigator of an ongoing effort in which the physics within each module will be improved upon by the experts in that field. The first incremental refinement made was to include a non-trivial treatment of the SH: the resulting program, dubbed TRIPTYCH[3], uses the Make Me A Star (MMAS) software package to determine mass loss during collisions as well as the structure and composition profiles of collision products. MMAS implements fast fluid-sorting algorithms to treat nearly parabolic encounters between low-mass main sequence stars (Lombardi et al., 2002). The source code for both MMAS and TRIPTYCH is freely available from their web sites.

In order to improve the SE in TRIPTYCH, Hurley wrote wrappers to his single-star evolution (SSE) code (Hurley et al., 2000), closely following the SE interface defined by Hut and Makino. The SSE routines use analytic fitting formulae to approximate accurately the evolution for a broad range of stellar masses and metallicity. For the SH to interface with these SE routines, it is still necessary to assume that the product becomes fully mixed immediately after the collision, an assumption that cannot be relaxed until a live SE code is introduced.

TRIPTYCH can be run online via a web interface, originally developed by Vicki Johnson of Interconnect. The user simply chooses two stellar models from a drag-down list, and enters values for a relative velocity, periastron separation and initial separation of the parent stars. Within just a few seconds, the output of TRIPTYCH is displayed, including plots of the orbital dynamics of the parent stars, as well as the stellar profiles and the subsequent evolutionary track on an HR diagram for the collision product.

An outgrowth of TRIPTYCH is a sister program, called TRIPLETYCH[4], that simulates the interaction of three stars, including the orbital trajectories, possible merger(s), and the subsequent evolution of the merger product. TRIPLETYCH is one star closer than its counterpart TRIPTYCH toward a realistic simulation of a star cluster. McMillan has implemented the SD of the three parent stars in TRIPLETYCH using the scatter3 routine from STARLAB, with visualizations generated by the snap_to_image routine. Two of the stars are initially bound, with the third approaching from infinity. The scattering package is described in detail by McMillan and Hut (1996). All orbital parameters may be specified by the user; those left unset are chosen randomly from appropriate distributions.

All STARLAB scattering packages (scatter3 and its higher-order generalizations) compute an encounter until it is unambiguously over—that is, two 'stable' objects are receding from one another with positive velocity at infinity. A stable object is a star or merger product, or any binary or dynamically stable multiple whose components are themselves stable. Within TRIPLETYCH, the software automatically detects collisions and close encounters,

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classifies the dynamical state of the system, and passes all data to the SH module. Currently, the dynamical calculation is resumed (via a simple Kepler solver in the three-body case, or by reverting to the scattering package in more complex configurations) once dynamical equilibrium is restored, as determined by MMAS. Should a second collision occur, the structure of the new triple merger product is computed similarly. Once no further interactions are indicated, the SE module is employed to determine the long-term evolution of the resulting object(s).

The separation of functionality just described is consistent with the characteristic time scales expected for the dynamical, hydrodynamical, and stellar-evolutionary processes involved in a simple three-body scattering. However, for more complex interactions, it will probably be desirable to integrate the three modules more closely, for example using the SE interfaces defined in MODEST-1 and implemented in TRIP(LE)TYCH by Hurley, including equivalent prescriptions for the evolution of newly merged systems not yet in thermal equilibrium.

TRIPLETYCH can also be run online via a Web interface. To start the simulation the user must choose the parent stars involved, set the velocity at infinity and impact parameter of the outer orbit, and set the semi-major axis and eccentricity of the inner orbit. All other orbital parameters are chosen at random (but the random seed may be specified to allow reproducible results). The Web interface will be expanded as the description of the underlying physics is refined.

There are still a number of improvements that can be made to these programs. It is hoped that web interfaces and free source code will continue to encourage collaborations as the modules are improved. The SD should ultimately be able to handle a true many-body system. MMAS should be replaced with a more general SH module that, among other improvements, allows for the possibility that the two stars do not merge. The SE code should be replaced with one that uses the full structure and chemical composition information provided by the SH module. Furthermore, the SE module will be expanded to allow for aspects of close binary evolution such as stable mass transfer, tidal interaction, and gravitational radiation, to name a few (see also Section 4.1).

3. Science goals

MODEST was first conceived to address scientific problems concerning old globular clusters. It became clear that the MODEST approach was applicable and relevant to more astrophysical situations than just globulars, however, including galactic nuclei, young star clusters and star forming regions. At MODEST-2, these science goals were explored in more detail. In the following section, observations (mostly of young objects) with relevance to the MODEST collaboration are discussed, along with the questions they raise. Sections 3.2 and 3.3 explore the questions and some possible solutions to an additional science goal of the MODEST collaboration—that is, the specification of reasonable and realistic initial conditions for models of all dense stellar systems.

3.1. Observational motivations

1. The observed high binarity and multiplicity of massive stars (for visual binaries see Mason et al., 1998; Preibisch et al., 2000; for spectroscopic binaries in clusters see García and Mermilliod, 2001) raises the question whether this is due to initial cloud or disk fragmentation or due to early dynamical evolution (Zinnecker, 2002). In particular, the surprising excess of short-period (5–7 days) massive double lined spectroscopic binaries in some young clusters calls for an explanation. Is it due to tidal capture (Zinnecker and Bate, 2002) or due to N-body evolution (Bate et al., 2002)?

2. In clusters with few massive stars, observations show that central Trapezium systems are a common feature (García and Mermilliod, 2001). Why is this so, and what is the dynamical evolution of Trapezium-like configurations? A series of N-body models with different initial conditions may help to answer the last question. However, the initial configurations can be very complex. For example, in the Orion Trapezium Cluster at least one of the Trapezium members is itself a Trapezium-like subsystem, and the other members (except θ Ori 1D) are binary or triple systems (see, e.g. Preibisch et al., 2000; Schertl et al., 2003).

3. The observed mass segregation in the Orion Trapezium cluster (Hillenbrand, 1997) and other clusters such as NGC 3603 and the Arches

(Eisenhauer et al., 1998; Stolte et al., 2002) as well as the exciting star cluster R136 of the 30 Dor giant HII region (Brandl et al., 1996) raises the question if this segregation is from birth ('primordial') or due to fast dynamical evolution. Bonnell and Davies (1998) did simulations to confirm that the Trapezium Cluster does not have the time to evolve dynamically and that the mass segregation must be primordial, but their Nbody2 calculations should perhaps be repeated with Nbody6 (to check whether a smaller softening parameter of the gravitational force matters for mass segregation or not). In addition, a realistic primordial binary population should be included. The Nbody6 computations of an ONC-like cluster by Kroupa (2002) suggest that the observed mass segregation may be obtained dynamically if the embedded cluster is dense enough, but this issue needs further study.

4. The observed location of the massive IRS16 group of stars as well as the well-known HeI emission line stars (Allen and Burton, 1994; Krabbe et al., 1995; Genzel et al., 2000) close to the Galactic Center is another challenging question: were they formed there or swept into the inner few parsec region by some sort of disrupted cluster? The latter is likely, as Portegies Zwart et al. (2002) have shown in their recent simulation. However, the issue remains as to how close to a galactic center a massive star cluster can form given the strong tidal field. For example the Arches cluster did form only 30 parsec from our Galactic Center, and its tidal radius is only about 2.5 parsec.

5. The observed field binary statistics (frequencies, separations, and mass ratios) of low-mass and intermediate mass stars (F to B) must be compared with the binary statistics in open clusters (e.g. in M16 see Duchêne et al., 2001) and OB associations (e.g. in Sco OB2 see Brown, 2001) in order to tackle the question of which mix of progenitor binary populations will provide the correct field star binary population (this was called 'inverse binary population synthesis' in Section 3.3, see also Ghez, 2001; Köhler, 2003). By understanding the dynamical evolution and dispersal of binary populations in young clusters and associations, can we retrace the origin of the field stars in general?

6. The observational statistics of runaway OB stars raises the question of whether isolated OB stars exist or whether they are the products of dynamical ejection from a nearby star cluster. Two good examples where B0 stars may have been ejected from young embedded protoclusters are the S255 and MonR2 clusters (Zinnecker et al., 1993; Carpenter, 2000); and Clarke and Pringle (1992) suggest that the OB runaways are inconsistent with a standard IMF in a young open cluster. Are these unusual cases, or the norm?

7. A large number of millisecond pulsars in globular clusters (e.g. 47 Tuc, Robinson et al., 1995) have been observed. This raises the question about what happened in the first fews tens of Myr in a young globular cluster. Were there several periods of star formation in globular clusters, i.e. extended periods where stars and gas would coexist? Which effects would the hybrid evolution of bound gas and stars suffer (drag, revirialisation of the core, shrinkage, etc.)?

8. The observed null result of radial velocity variations in 34 000 stars in 47 Tuc (in an attempt to search for giant planets, Gilliland et al., 2000) raises the question of the fate of any planetary mass companions in dense globular clusters. Have they never formed or have they all been ejected, creating a population of free-floating planets in those clusters? See Davies and Sigurdsson (2001) and Hurley and Shara (2002) for relevant simulations.

To turn the idea of observational motivation around, H. Zinnecker posed the question: Which kind of HST observations could the MODEST consortium propose (as a group) to seriously test some of their results? For example NICMOS observations on embedded protoclusters should be conducted, such as the one associated with the HII region G308.70 + 0.60 at 5 kpc, 10 times nearer than 30 Doradus (Cohen et al., 2002).

The following simulations were also proposed as being of strong interest to observational questions: (1) simulate dynamical evolution of toy globular clusters with a truncated IMF (e.g. no stars below $1 M_\odot$, no stars below $0.5 M_\odot$, no intermediate-mass stars, or some other semi-ridiculous situation); (2) simulate stellar population synthesis (for galaxies) with and without interacting binaries (see Portegies Zwart et al., 2001a,b).

Though the above issues concentrate on young stellar systems, much of the work of MODEST is directed to old objects, especially globular clusters. One of the classical, observationally motivated problems here is the construction of dynamical models. For a long time this was dominated by King models and its variants, but *evolutionary* models have been constructed for a number of objects. One issue here is how one selects initial conditions that lead, after 12 Gyr of dynamical and stellar evolution, to models that fit the present observed structure.

Towards this goal, M. Giersz, E. Vesperini and D. Heggie will be working on the modelling of specific globular clusters, i.e. attempting to fit the surface brightness profile, mass functions and radial velocity dispersion profile. So far this has been done by Monte Carlo modelling without binaries (Giersz and Heggie, 2003), and their intention is to extend this by: (a) incorporating binary populations in the Monte Carlo code (see Section 4.1 below); and (b) cross-checking the results by the slower but less approximate *N*-body method (Section 5).

3.2. Initial conditions

In order to follow the evolution of a dense stellar system, one has to know (or choose) the initial conditions of that system. Traditionally, the starting point for a dynamical simulation has been a Plummer model or a King model. The system includes only stars that are on the zero-age main sequence and distributed evenly throughout the cluster, and no gas, star formation, or proto-stellar disks. We know that most of these assumptions are at best simple and at worst downright wrong. In this section, we outline the results of star formation and molecular cloud evolution calculations that are relevant for the initial conditions of star cluster evolution simulations.

Modern star formation theory considers supersonic interstellar turbulence, ubiquitously observed in star forming molecular clouds, as controlling agent for stellar birth, rather than mediation by magnetic fields as was previously assumed, but which fails to predict many of the observed properties of star forming clouds (Whitworth et al., 1996; Nakano, 1998; Crutcher, 1999; Bourke et al., 2001; André et al., 2000; Mac Low and Klessen, 2003).

The key point to this new understanding lies in the properties of interstellar turbulence that is typically

supersonic as well as super-Alfvénic. It is energetic enough to counterbalance gravity on global scales, but at the same time it may provoke local collapse on small scales. This apparent paradox can be resolved when considering that supersonic turbulence establishes a complex network of interacting shocks, where converging flows generate regions of high density. This density enhancement can be sufficiently large for gravitational instability to set in. The same random flow that creates density enhancements, however, may disperse them again. For local collapse to result in stellar birth, it must progress sufficiently fast for the region to 'decouple' from the flow. Typical collapse timescales are therefore of the same order as the lifetimes of shock-generated density fluctuations in the turbulent gas. This makes the outcome highly unpredictable. As stars are born through a sequence of stochastic events, any theory of star formation is in essence a statistical one with quantitative predictions only possible for an ensemble of stars.

In this new picture, the efficiency of protostellar core formation, the growth rates and final masses of the protostars, essentially all properties of nascent star clusters depend on the intricate interplay between gravity on the one hand side and the turbulent velocity field in the cloud on the other. The star formation rate is regulated not just at the scale of individual star-forming cores through ambipolar diffusion balancing magnetostatic support, but rather at all scales (Elmegreen, 2002), via the dynamical processes that determine whether regions of gas become unstable to prompt gravitational collapse. The presence of magnetic fields does not alter that picture significantly (Mac Low et al., 1998; Stone et al., 1998; Padoan and Nordlund, 1999; Heitsch et al., 2001), as long as they are too weak for magnetostatic support, which is indicated by observations (Crutcher, 1999; Bourke et al., 2001). In particular, magnetic fields cannot prevent the decay of interstellar turbulence, which in turn needs to be continuously driven or else stars form quickly and with high efficiency

Inefficient, isolated star formation will occur in regions that are supported by turbulence carrying most of its energy on very small scales. This typically requires an unrealistically large number of driving sources and appears at odds with the measured velocity structure in molecular clouds which in

almost all cases is dominated by large-scale modes. The dominant pathway to star formation therefore seems to involve cloud regions large enough to give birth to aggregates or clusters of stars. This is backed up by careful stellar population analysis indicating that most stars in the Milky Way formed in open clusters with a few hundred member stars (Kroupa, 1995; Adams and Myers, 2001).

Clusters of stars build up in molecular cloud regions where self-gravity overwhelms turbulence, either because such regions are compressed by a large-scale shock, or because interstellar turbulence is not replenished and decays on short timescales. Then, many gas clumps become gravitationally unstable synchronously and start to collapse. If the number density is high, collapsing gas clumps may merge to produce new clumps that now contain multiple protostars. Mutual dynamical interactions become common, with close encounters drastically altering the protostellar trajectories, thus changing the mass accretion rates. This has important consequences for the stellar mass distribution. Already in their infancy, i.e. in the deeply embedded phase, very dense stellar clusters are expected to be strongly influenced by collisional dynamics (Bonnell et al., 1997, 2001a,b; Klessen and Burkert, 2000, 2001; Klessen, 2001a,b).

In the following we list some of the recent observational and theoretical findings that are directly relevant to formation and evolution of star clusters.

- Star clusters are expected to build up fast, i.e. on timescales of order of the free-fall time τ_{ff} (e.g. Klessen et al., 2000; Bate et al., 2002), as opposed to the much longer ambipolar diffusion timescale proposed by the 'standard' theory of magnetically mediated star formation (Shu, 1977; Shu et al., 1987). Indeed, the observed age spread of stars in young clusters is exactly of order τ_{ff} (for Taurus see Hartmann, 2001, 2002, however, consider also Palla and Stahler, 1999, 2002; for the Trapezium cluster in Orion see Hillenbrand, 1997 or Hillenbrand and Hartmann, 1998). For calculations of the subsequent dynamical evolution of star clusters this has the important consequence that there is a relatively well defined starting time.

- The pre-main sequence timescale for low-mass

stars can reach several tens of millions of years. That means that during an initial period of a few $\times 10^7$ years the population of young stellar clusters contains both main sequence (MS) as well as pre-main sequence (PMS) stars. As PMS stars in general have considerably larger radii than MS stars (e.g. Palla, 2000), the effects of stellar collisions will be strongly enhanced during the first few million years of cluster evolution (see e.g. the discussion in Bonnell et al., 2001a,b). This is not taken into account in any of the current star cluster evolutionary calculations.

- It remains quite unclear what terminates stellar birth on scales of individual star forming regions. Three main possibilities exist. First, feedback from the stars themselves in the form of ionizing radiation and stellar outflows may heat and stir surrounding gas up sufficiently to prevent further collapse and accretion. Second, accretion might abate either when all the high density, gravitationally unstable gas in the region has been accreted in individual stars, or after a more dynamical period of competitive accretion, leaving any remaining gas to be dispersed by the background turbulent flow. Third, background flows may sweep through, destroying the cloud, perhaps in the same way that it was created. Most likely the astrophysical truth lies in some combination of all three possibilities.

- Most relevant to the formation of rich clusters is gas expulsion by radiation and winds from massive stars. The UV flux from O/B stars ionizes gas out beyond the local star forming region. Ionization heats the gas, raising its Jeans mass, and possibly preventing further protostellar mass growth or new star formation. The termination of accretion by stellar feedback has been suggested at least since the calculations of ionization by Oort and Spitzer (1955). Whitworth (1979) and Yorke et al. (1989) computed the destructive effects of individual blister HII regions on molecular clouds, while in series of papers, Franco et al. (1994), Rodriguez-Gaspar et al. (1995), and Diaz-Miller et al. (1998) concluded that indeed the ionization from massive stars may limit the overall star forming capacity of molecular clouds to about 5%. Matzner (2002) analytically modeled the effects of ionization on molecular

clouds, concluding as well that turbulence driven by HII regions could support and eventually destroy molecular clouds. Focusing on the dynamical evolution of young star clusters subject to sudden gas removal, Kroupa et al. (2001) demonstrated the existence of an evolutionary sequence that connects massive embedded star clusters with the Orion nebula cluster and the Pleiades. These models treat cluster gas only in form of a smooth and time-varying background potential. The key question remains, however, whether HII region expansion couples efficiently to clumpy, inhomogeneous molecular clouds. This can only be addressed with combined hydro- and stellar dynamical models (see Geyer and Burkert, 2001 for a first attempt).

- The theory of turbulent cloud fragmentation furthermore predicts massive stars to form towards the cluster center while lower-mass stars will build up more dispersed (e.g. Klessen, 2001b). Star clusters are thus believed to have a considerable degree of mass segregation already in their embedded phase. This is in agreement with recent finding in very young stellar clusters that often exhibit a degree of mass segregation that cannot be explained by subsequent dynamical evolution, as e.g. observed in NGC 330 in the Small Magellanic Cloud (Sirianni et al., 2002).

- Star clusters are also expected to form with a high degree of substructure (e.g. Klessen and Burkert, 2000). This is indeed observed in almost all low-mass star forming regions (for Taurus see e.g., Mizuno et al., 1995 or Hartmann, 2002; for ρ Ophiuchus see Motte et al., 1998 or Bontemps et al., 2001) and constitutes an important aspect of their further dynamical evolution. In rich clusters, however, the relaxation timescales are shorter, and such clusters will thus experience a considerable degree of relaxation and erasure of substructure already in the embedded phase, i.e. before the cluster becomes fully visible at optical wavelengths. Focusing on the Trapezium cluster this issue has been discussed by Scally and Clarke (2002).

- Stars typically form as parts of a binary or higher-order multiple system. For the Galactic field stars in the solar neighborhood the binary frequency is estimated to be about 50% (Duquennoy and Mayor, 1991), the fraction observed in young star clusters typically is comparable to that (e.g. in the Trapezium, Prosser et al., 1994; Petr et al., 1998), but may reach values as high as 100% in dilute regions of low-mass star formation (e.g. in Taurus, Leinert et al., 1993; Ghez et al., 1993; Köhler and Leinert, 1998). For further references consult the review by Mathieu et al. (2000). This is expected from turbulent fragmentation models, and is consistent with cluster evolution calculations having a high fraction of 'primordial' binaries (e.g. Kroupa, 1998, or Kroupa et al., 1999).

3.3. An example of a standard reference star-formation model

In the work of Kroupa and collaborators, a particular set of initial parameters has emerged as a kind of standard model. A brief description of those parameters is presented here. It is useful as standardised and realistic initial conditions for *N*-body computations of star clusters. The standard model is defined by a minimal set of assumptions based on empirical and theoretical evidence that describe the outcome of star formation. The model has been developed in Kroupa (1995) = K2 by applying inverse dynamical population synthesis to find the dominant star-formation events that produced the Galactic field population, taking as an initial boundary condition the observed pre-main sequence binary-star properties in Taurus-Auriga. It accounts for the properties of short-period binary systems, but does not incorporate brown dwarfs. In the strict form, it therefore only applies to late-type stars. This model leads to stellar populations in good agreement with available observational evidence for Galactic-field stars and pre-main sequence stars in dense clusters (K2; Kroupa et al., 2001).

The standard model can be used to search for variations of the IMF or binary-star properties with star-formation conditions. If a population is found which has an abnormal IMF or unusual binary-star properties, and if dynamical and stellar evolution cannot reproduce these observations given the standard model, then a very strong case for a variation of the IMF or binary-star properties has been found. An

example of such an application is provided by Kroupa (2001).

The standard model assumes:

1. All stars are paired randomly from the IMF to form binary systems with primary mass m_p and companion or secondary mass $m_s \leq m_p$.
2. The distribution of orbital elements (period, eccentricity and mass ratio) does not depend on the mass of the primary star, but allowance for eigenevolution (see below) is made.
3. Stellar masses are not correlated with the phase-space variables (no initial mass segregation in a cluster).

Assumption 1 leads to a flat initial mass-ratio distribution for late-type primaries, f_q, (Fig. 12 in K2), and is in good agreement with the flat mass-ratio distribution for $q \equiv m_2/m_1 > 0.2$ derived from observational data of pre-main sequence binaries by Woitas et al. (2001). They state that 'these findings are in line with the assumption that for most multiple systems in T associations the components' masses are principally determined by fragmentation during formation and not by the following accretion processes'. This in turn is supported by the finding that the mass function of pre-stellar cores in ρ Oph already has the same shape as the Galactic-field IMF, thus indicating that the fragmentation of a molecular cloud core defines the distribution of stellar masses (Motte et al., 1998; Bontemps et al., 2001; Matzner and McKee, 2000). By extending the standard model to include brown dwarfs, the stellar pairing properties are changed by allowing stars to have brown dwarf companions. The fraction of such systems may be appreciable but depends on the IMF for brown dwarfs. Likewise, extension of the standard model to massive stars implies that most O stars will have low-mass companions.

Assumption 2 is posed given the indistinguishable period distribution function of Galactic-field G-dwarf, K-dwarf and M-dwarf binary systems (Fig. 7 in K2). The discordant period distributions between the pre-main sequence binaries and the Galactic-field systems can be nicely explained by disruption of wide-period binaries in small embedded clusters containing a few hundred stars. This destruction process also leads to the observed mass-ratio distribution for G-dwarf primaries in the Galactic field. The model is also in good agreement with the

observed smaller binary fraction of M dwarfs than of K dwarfs and G dwarfs.

Assumption 3 allows investigation of the important issue whether massive stars need to form at the centres of their embedded clusters to explain the observed mass segregation in very young clusters such as the ONC. Assumption 3 is motivated by observations that indicate that at least some massive stars appear to be surrounded by massive disks (e.g. Figueredo et al., 2002) suggesting growth of the massive star by disk accretion rather than through coagulation of proto-stars, and by the observations that forming embedded clusters are typically heavily sub-clustered, with massive stars forming at various locations (e.g. Motte et al., 2002). On-going N-body work is addressing the issue if dynamical mass-segregation can account for the observed mass segregation in the ONC for example, but the alternative scenario is that coagulation of forming proto-stars in the densest embedded cluster region with continued accretion of low-angular momentum material onto the forming cluster core leads to the build-up of a core of massive stars there (Bonnell et al., 1998; Klessen, 2001b).

The initial distribution functions that are needed to describe a stellar population are the IMF, the period and eccentricity distribution functions. The IMF is conveniently (for computational purposes) taken to be a multi-power-law form,

$$\xi(m) =$$

$$k \begin{cases} \left(\frac{m}{m_H}\right)^{-\alpha_0}, & m_l < m \leq m_H, \\ \left(\frac{m}{m_H}\right)^{-\alpha_1}, & m_H < m \leq m_0, \\ \left[\left(\frac{m_0}{m_H}\right)^{-\alpha_1}\right]\left(\frac{m}{m_0}\right)^{-\alpha_2}, & m_0 < m \leq m_1, \\ \left[\left(\frac{m_0}{m_H}\right)^{-\alpha_1}\left(\frac{m_1}{m_0}\right)^{-\alpha_2}\right]\left(\frac{m}{m_1}\right)^{-\alpha_3}, & m_1 < m \leq m_2, \\ \left[\left(\frac{m_0}{m_H}\right)^{-\alpha_1}\left(\frac{m_1}{m_0}\right)^{-\alpha_2}\left(\frac{m_2}{m_1}\right)^{-\alpha_3}\right]\left(\frac{m}{m_2}\right)^{-\alpha_4}, & m_2 < m \leq m_u, \end{cases}$$

$$(1)$$

where k contains the desired scaling, and $dN = \xi(m)\,dm$ is the number of stars in the mass interval m to $m + dm$. Eq. (1) is the general form of a five-part power-law form, but at present observations only support a three-part power-law IMF (Kroupa, 2002) with $m_l = 0.01\,M_\odot$, $m_H = 0.08\,M_\odot$, $m_0 = 0.5\,M_\odot$, and $\alpha_2 = \alpha_3 = \alpha_4$,

$$\alpha_0 = +0.3 \pm 0.7, \quad 0.01 \leq m/M_\odot < 0.08,$$
$$\alpha_1 = +1.3 \pm 0.5, \quad 0.08 \leq m/M_\odot < 0.50, \quad (2)$$
$$\alpha_2 = +2.3 \pm 0.3, \quad 0.50 \leq m/M_\odot.$$

The multi-part power-law form is convenient because it allows an analytic mass-generation function to be used which leads to very efficient generation of masses from an ensemble of random deviates. The multi-part power-law form also has the significant advantage that various parts of the IMF can be changed without affecting other parts, such as changing the number of massive stars by varying α_4 without affecting the form of the luminosity function of low-mass stars. Other functional descriptions of the IMF are in use (e.g. Chabrier, 2001).

A convenient form for the initial period distribution function that has an analytic period-generation function is derived in K2,

$$f_{P,birth} = 2.5 \frac{(lP - 1)}{(4 + (lP - 1)^2)}, \quad (3)$$

where $f_{P,birth} \, dl P$ is the proportion of binaries among all systems with periods in the range lP to $lP + dl P$ (P in days), and $1 \leq lP \equiv \log_{10} P$. The usual notation for the binary proportion is used here, $f_P = N_{bin,P}/N_{sys}$, where $N_{sys} = N_{bin} + N_{sing}$ is the number of systems and $N_{bin,P}$ is the number of binary systems with periods in the bin lP. The condition $\int_{lP} f_{P,birth} = 1$ (all stars being born in binaries) gives $P_{max} = 10^{8.43}$ d for the maximum period obtained from the distribution given in Eq. (3). N-body experiments demonstrate that the observed range of periods ($P \approx 10^{0-9}$ d) must be present as a result of the star-formation process; encounters in very dense subgroups cannot sufficiently widen initially more restricted period distributions and at the same time lead to the observed fraction of binaries in the Galactic field (Kroupa and Burkert, 2001). Observations show that the eccentricity distribution of Galactic-field binary systems is approximately thermal, $f_e = 2e$, and N-body calculations demonstrate that such a distribution must be primordial because encounters of young binaries in their embedded clusters cannot thermalize an initially different distribution (K2; Kroupa and Burkert, 2001).

Binary systems in the Galactic field with short periods ($P \lesssim 10^3$ d) do show departures from simple pairing by having a bell-shaped eccentricity dis-

tribution and a mass-ratio distribution that appears to deviate from random sampling from the IMF. This is apparent most dramatically in the eccentricity-period diagram that shows an upper eccentricity-envelope for short-period binaries (Duquennoy and Mayor, 1991). This indicates that binary-system–internal processes may have evolved a primordial distribution. Such processes are envelope–envelope or disk–disk interactions during youth, shared accretion during youth, rapid tidal circularisation during youth, and slow tidal circularisation during the main-sequence phase. These system-internal processes that change the orbital parameters cannot be expressed with only a few equations given the extremely complex physics involved, but a simple analytical description is available through the K2-formulation of *eigenevolution-feeding*. Feeding allows the mass of the secondary to grow, while eigenevolution allows the eccentricity to circularise and the period to decrease at small peri-astron distances, and merging to occur if the semi-major axis of the orbit is smaller than 10 Solar radii. About 3 per cent of initial binaries merge to form a single star. The eigenevolved model-main-sequence eccentricity–period diagram, and the eccentricity and mass-ratio distributions of short-period systems, agree well with observational data. In particular, although the minimum period obtained from Eq. (3) is $P = 10$ d, eigenevolution leads to the correct number of $P < 10$ d periods. The resulting IMF of all stars shows slight departures from the input IMF (Eq. (2)) as a result of the mass-growth (feeding) of some secondaries, but the deviations are well within the IMF uncertainties.

4. Modelling goals

4.1. Interfaces

A recurring theme throughout the meeting was the desirability of multiple versions of different kinds of physics (dynamics, stellar evolution, binary evolution, etc.) that were completely modular, so that they could be swapped in and out, in different combinations, to test the robustness of our conclusions. A workable approach to this issue is the specification of appropriate interfaces.

MODEST-1 defined a simple but robust interface

between dynamical and (single-star) stellar evolutionary modules (Hut et al., 2003). The intent was to construct a 'minimally invasive' standard means for dynamical integrators to communicate with stellar evolutionary codes, without placing any restrictions on the internal language, structure, or algorithms of either. Hurley's implementation of this interface for use within TRIPTYCH and TRIP-LETYCH is a promising indicator of the basic soundness of the approach. The N-body codes kira and NBODY4 each include a binary evolution algorithm and have successfully demonstrated that modelling of binary evolution in concert with stellar dynamics is vital for understanding the nature of stellar populations of star clusters (Hurley et al., 2001; Portegies Zwart et al., 2001a,b). However, each algorithm is drawn from a particular (and different) binary population synthesis code, i.e. the approach to this point has been distinctly non-modular, and computational constraints have limited the N-body method to small-N so far. Full proof of concept will be realized when the interface is incorporated into the N-body codes and the equivalent Monte-Carlo schemes, in principle allowing stellar evolutionary algorithms to be exchanged between radically different dynamical integrators.

One goal that came out of MODEST-2 concerned the variety of binary evolution packages that exist. We would like to be able to include binary evolution into any dynamics code that exists, be it N-body, gas, Monte Carlo or whatever. Therefore, there was a call for a standardized interface between binary evolution and dynamics calculations, along the lines of the standardized single star evolution interface developed after MODEST-1. Although the detailed information that may be needed is more complex and the range of possible evolutionary states is much broader, we believe that a simple interface similar in spirit to that already developed for stellar evolution is feasible.

As an illustration of how this can be done, after the meeting S. Portegies Zwart and D. Heggie constructed an example showing how the binary evolution packages in starlab can be integrated with some other code. For this purpose they constructed a simple three-body scattering package, based on the scattering cross sections used by Giersz (1998, 2001) in his Monte Carlo code, and added the binary evolution routines from starlab. The resulting code, called McScatter (for Monte Carlo scatter) has been made available on the MODEST web site, and further developments are planned.

While the simple code that is being devised by Portegies Zwart and Heggie is intended for illustrative purposes only, a more elaborate code of this kind already exists. In a recent project at Northwestern University, N. Ivanova, K. Belczynski, V. Kalogera and F. Rasio start with a sophisticated population synthesis code (which can calculate accurately the evolution of a large population of non-interacting single and binary stars) and add to it a simplified treatment of dynamical interactions between stars and binaries in a dense cluster environment. In the Northwestern project, all relevant interactions (collisions, binary–single and binary–binary) are implemented in a Monte Carlo fashion and with simple recipes for determining the outcomes. The cluster is modeled as a static background and all interactions are assumed to take place in a core of fixed size and density. This approach to study the evolution of the stellar population in a dense cluster core has two main advantages: (1) it is very fast (the computational time is spent almost entirely for the evolutionary calculations; the evolution of 10^5 binaries for a Hubble time can be calculated in about 2 days on a single 2Ghz Pentium IV processor); (2) the dependence of the resulting stellar population on the dynamics and cluster parameters can be studied easily and systematically, e.g., by turning on or off one dynamical effect at a time. Among the many planned applications of this approach is a new study of the formation and evolution of low-mass X-ray binaries and millisecond pulsars in globular clusters. The population synthesis code that this project used as a starting point is the StarTrack code developed by K. Belczynski and V. Kalogera (Belczynski et al., 2002). This code evolves binaries using standard prescriptions for population synthesis studies with improved detailed treatments of many important processes affecting the stellar evolution and binary orbits: common envelope evolution (based on an $\alpha_{CE}\lambda$-type prescription) and complete binary mergers; detailed treatment of stable and unstable, conservative and non-conservative mass transfer phases, thermal timescale mass transfer; tidal dissipation, synchronization and circularization; mass

and angular momentum loss through stellar winds; angular momentum loss through gravitation radiation and magnetic breaking; hyper-critical accretion onto compact objects, asymmetric core-collapse events, SN explosions and kicks.

4.2. Primordial triple and multiple systems

The incidence of triple and higher-multiple systems in the solar neighborhood is by no means neglible: probably between 5 and 15% of systems are at least triple. A cross-referencing of the catalogue of 612 multiple stars by Tokovinin (1997) with the Bright Star Catalogue (BSC; Hoffleit and Jaschek, 1983; the 9110 brightest stars, more or less) gives 395 entries in common. This shows clearly how incomplete the data must be, and suggests that 5% is very much a lower bound. Much smaller but more thoroughly studied samples suggest that 10% is reasonable, but with considerable uncertainty.

It is not clear to what extent these should be considered 'primordial'. Some might be produced in dense star-forming regions (SFRs) by binary–binary dynamical interactions, but dynamical evolution of clusters containing even a high proportion of primordial binaries do not generally produce as many triples as are observed (e.g. Kroupa, 1995). Direct observation of SFRs suggests that triples are even more common in them than in the field. Consequently it seems likely that on balance triples are destroyed rather than created in dynamical encounters. It seems reasonable therefore that until a really detailed understanding of star formation can give the observed frequency of binaries *and* triples, we should start dynamical calculations with a distribution of primordial triples as well as binaries.

Most of the triples in the field, however, are wide systems where the outer orbits are of size $\gtrsim 100$ AU, and should be relatively quickly destroyed in dense stellar environments. However, a proportion have *outer* orbits of $\lesssim 10$ AU, and these may be hard enough to survive for some time, and to influence both dynamical and stellar evolution in dense clusters. A provisional estimate is that 1–2% of systems in the solar neighborhood have outer orbits $\lesssim 10$ AU. The proportion seems to be larger among systems of higher mass (OBA) than lower mass (FGK). We might note that among the ~ 50 O

stars brighter than 6th magnitude, τ CMa is a triple (van Leeuwen and van Genderen, 1997) with an *outer* period of only 155d; actually, the system is quadruple, with a fourth body at a few hundred AU. Among similarly bright B stars λ Tau has an outer period of only 33d (Fekel and Tomkin, 1982). We can list about 50 of the BSC triple stars in which the outer period is less than ~ 10 yr, and the census is by no means complete since third components in orbits of $1 - 10$ yr are usually quite hard to recognise. The detection rate of such triples appears to be currently of order one per year: a recent bright addition is δ Lib (Worek, 2001), a classic Algol that turns out to have a third body in an orbit of ~ 1000 d.

Triples are likely to be important both for dynamical and for stellar-evolutionary reasons. Dynamically, this is because they are usually of higher mass and so are more likely to sink to the centre. The triple HD109648 (Jha et al., 2000) consists of three F stars of very similar masses, with periods of 5.5 and 120 d. Such a system in a moderately old dense cluster should have an important effect on the dynamical evolution of the cluster. Evolutionarily, the same system could be important as a potential blue straggler with as much as three times the turn-off mass. But there are several other evolutionary channels that are open to such triples, but not to binaries.

4.3. Lusus naturæ

In this section we discuss a few special cases for which we have little understanding and for which no obvious modelling technique currently exists. The main reason to add this section is to prompt new research. Most special cases in MODEST originate either on the interface between two well-developed techniques or due to the effect one part of the model has on the other. These may lead to unexplored areas of physics or to monstrosities (*lusus naturæ*). We therefore do not intend to discuss uncertainties in the various modelling techniques, such as the mixing length in stellar evolution, the common envelope parameter in binary evolution or the energy generation of shocks in hydrodynamical calculation.

We have encountered so many bizarre situations in current models that we cannot list them all in this section; nor can we anticipate on all possible pro-

cesses and creation for which no ready continuation of the model calculations exists. Instead, we will illustrate the *lusus naturæ* with a few interesting cases.

The most obvious interface problem comes from the improvement in stellar physics, from single stellar evolution to binary evolution. Many publications have been written about the *zoo* which originates when two stars are evolved synchronously while taking variations in the orbital parameters into account. The introduction of stellar dynamics to binary evolution leads to all kinds of extra interface problems and to an enormous enlargement of the possibility of non-standard cases. Some of the most obvious curiosities when stellar evolution, binary evolution and stellar dynamics are combined are binaries with two blue stragglers, a blue straggler more than twice the turn-off mass or two close white dwarf binaries in eccentric orbits. These cases are rather rare, and in general we are quite well equipped to handle such situations.

The real *lusus naturæ* are these cases where no ready methodology is available. An example of this is mass transfer in binaries which are strongly perturbed by a third star. Such binaries can easily pick up some eccentricity in the interaction, which then can affect the characteristics of mass transfer quite dramatically. There is very little theoretical understanding of the mass transfer in eccentric binaries, in part because we have no clear examples in the solar neighborhood which we can study. For this reason also, these cases do not always attract the attention they require.

On the interface between gas dynamics and stellar dynamics are several instances for which there is currently no methodology available. What happens, for example, to the mass liberated in the low velocity stellar wind of a low-mass star on asymptotic giant branch? Generally it is assumed that this gas is blown out of the star cluster and that its effect on the stellar motions is negligible. However, in galactic nuclei, for example, this residual gas can strongly affect the model calculations. It may even change the surface abundances of other stars in the cluster, as suggested by D'Antona et al. (2002). The main era in a cluster's life when gas is important is during its formation, as discussed in detail in Sections 3.2 and 3.3. It may be, however, that gas needs to be considered to some degree throughout the lifetime of the cluster.

The interface with hydrodynamics and other modes also poses many opportunities for *lusus naturæ*. Collisions between many stellar spectral types have been carried out, even between compact objects. And in some case the collision products are even further evolved with stellar evolution models. In these models a clear problem is the enormous amount of angular momentum which the merger product has to lose in order to become a relatively normal star again (see Section 4.4). In recent dynamical models it has become clear that runaway collisions can be quite common. The evolution of a single collision product is already quite uncertain, let alone a star which has experienced more than one collision. It is unclear what kinds of supernovae these runaway products will produce, or if they will be substantially unusual in any way. Finally, there are still some collisions we have not modelled in detail. Particularly, what happens when a newly-formed neutron star receives a kick from its supernova, and then immediately runs into a nearby companion? The canonical understanding is that it will become a Thorne–Zytkow object, but what does that look like? Is it something we can detect as strange?

As a last case, we mention the interaction between a star cluster and its direct gravitational environment, such as the tidal field of the Galaxy, other nearby star clusters or simply the swarm of field stars in the clusters' surrounding. The first case has been studied in some detail, but the others require more thought, particularly for studies of young star clusters near the galactic centre.

It is the goal of the MODEST collaboration to categorize and address these issues, and to develop the necessary tools to deal with these *lusus naturæ*. In this section, we have given a flavour of some of the issues that are yet to be addressed. We expect the list will continue to grow as the interfaces between stellar evolution, stellar dynamics and hydrodynamics become more fully entangled.

4.4. Stellar evolution of non-standard stars

One of the goals of the MODEST collaboration is to be able to evolve stellar collision products and

binary merger products on-the-fly when they are created during the dynamical evolution of a stellar system. The biggest problem with evolving these products is that they 'begin' their lives significantly out of thermal equilibrium, even if they are in hydrostatic equilibrium. For a description of evolution calculations of products of collisions between two main sequence stars (i.e. blue stragglers), see Sills et al. (1997) and Sills et al. (2001). They use the results of SPH simulations of collisions directly as starting models for stellar evolution calculations, and follow the collision product through the thermal relaxation phase to the main sequence and beyond. The results for head-on collisions are reasonable and robust. When the collisions are not head-on, however, the collision product has a significant amount of angular momentum from the initial orbit of the two parent stars. Since the 'proto-blue-straggler' does not have a surface convection zone, there is no obvious way for it to lose angular momentum (through a magnetic wind, for example). It needs to lose most of its angular momentum so that it does not reach break-up velocity as it contracts to the main sequence. A possible solution to this problem is to have the proto-blue-straggler create and retain a disk of material for a few Myr (probably the first material that is thrown off by the contraction of the rapidly rotating product). If the blue straggler can become locked to the disk during its contraction phase, or even a portion of it, the star will spin down by transfering angular momentum to the disk, in the same manner as protostars (Sills et al., 2000; Barnes et al., 2001). Preliminary calculations of this process are giving promising results.

When studying blue stragglers, it is also necessary to consider the blue stragglers that are formed from the primordial binaries (either initially close binaries, or ones that have undergone an exchange during a close encounter, as M. Davies discussed at MODEST-2). The structure, and hence subsequent evolution, of mass transfer remnants remains uncertain. Simulations of mass transfer and common envelope evolution are called for, so that the structure of the products can be determined accurately.

There are more stars in globular clusters than just main sequence stars. Giant branch stars, white dwarfs, even neutron stars are involved in collisions in the dense regions of clusters with significant regularity. Collisions involving giants, in particular, may explain some observations of globular clusters. The cores of dense globular clusters seem to be lacking in bright giants (Bailyn, 1994); some core collapse clusters show evidence for colour gradients, in the sense of being bluer in the centre (Djorgovski et al., 1991); and extreme horizontal branch stars (or sdB stars) seem to be concentrated towards the centres of dense clusters (Ferraro et al., 1992). The suggestion is that giants are involved in collisions in the densest regions of clusters. The collision removes some mass from the giant, prohibiting its ascent to the tip of the giant branch, and producing a low-mass (i.e. blue) horizontal branch star rather than a regular one. SPH simulations of collisions with giants, particularly those collisions that are mediated by a binary system, show that significant amounts of mass can be removed from the giant. Subsequent evolutionary calculations of both the stripped giant and the incoming star which removes the mass will constrain this scenario.

Detailed stellar evolution calculations of collision products, using hydrodynamics simulations to provide the starting conditions, are very useful for providing the basis for recipes of stellar collision product evolution, and for determining the best way for live codes to handle unusual configurations, particularly those out of thermal equilibrium. By creating and using detailed models, we can have more confidence in the results of the cluster evolution simulations.

5. Comparison and validation

The evolution of dense stellar systems is such a complicated problem that no exact solutions and few exact constraints are known. Therefore the reliability of simulations can best be checked by cross-validation. For this purpose we should aim to devise a small suite of well specified test problems, and to make available standard sets of results. These can be used to check that a new code is working correctly, or that approximate methods give results consistent with more elaborate methods.

Here, we summarise the kinds of problems according to the ingredients that they can be used to check. We concentrate on studies which have resulted in

tabular data, as without these the necessary comparisons tend to be rather qualitative. (For example, the evolution of an isolated Plummer model with stars of equal mass has been studied many times, but results are given usually in graphical form.) We also restrict attention to problems that have already been studied by more than one method or code.

5.1. Pure stellar dynamics—single stars

Though small ($N = 25$) by current N-body standards, the experiment reported by Lecar (1968) was the first example of a collaborative study, and made plain the chaotic evolution of the system.

The name 'first collaborative experiment' (Heggie et al., 1998; Heggie, 2003) is usually applied nowadays to a much later problem devised for the IAU General Assembly in Kyoto in, 1997. This experiment specified a reasonably rich ($N \simeq 2.5 \times 10^5$) system of unequal masses in a tidal field. This is too large for N-body models, which had to be scaled. This led to the interesting discovery that the dissolution time does not vary in proportion to the relaxation time, as is usually assumed, but varies more slowly with N (Baumgardt, 2001). Results are available on the web (http://www.maths.ed.ac.uk/douglas/experiment.html).

5.2. Pure stellar dynamics—binary and single stars

One of the Fokker–Planck models studied by Gao et al. (1991) has become a test case that has been used by Giersz and Spurzem (2000) to compare with results from a different (but still approximate) method. N-body results would be useful, but since $N \sim 3 \times 10^5$, this is not feasible at present. Giersz and Spurzem have also conducted comparisons with the N-body models of Heggie and Aarseth (1992), but these pre-GRAPE models are much too *small* to be useful nowadays.

There is a need for standardised N-body models in this area. The second collaborative experiment (Kyoto II, see below) assumes evolution of single and binary stars, but some partial calculations using stellar dynamics alone have been completed, all with N-body models, and it is hoped that this 'sub-Kyoto II' may meet this need.

5.3. Stellar dynamics and stellar evolution—single stars

A well specified set of models was formulated and studied by Chernoff and Weinberg (1990). This specification then became the basis of subsequent N-body studies by Aarseth and Heggie (1998), who used scaling with N. Other studies with this and other methods are presented by Takahashi and Portegies Zwart (2000), Giersz (2001) and Joshi et al. (2001).

5.4. Stellar dynamics and stellar evolution—single and binary stars

This is the domain of the Kyoto II collaborative experiment (Heggie, 2003), which is an example of a single well-specified problem that should be amenable to simulation by a wide variety of codes. It is a specification for the initial and boundary conditions of a rich (16 k) object with 25% binaries. Even though the initial conditions were agreed at IAU Symposium 208 in 2001, and even though there was considerable discussion and virtual unanimity about them at that time, progress has been much slower than with the first collaborative experiment. Indeed no complete calculation has been achieved so far, though there have been considerable numbers of 'partial' calculations, i.e. those which ignore some aspect of the problem, such as binary evolution, or calculations that differ in some other way from the correct specification. Some problems have been due to the specification of the tide as a cutoff rather than a field, though there were sound reasons for this choice. Others are due to the specification of the initial conditions in 'astrophysical' units rather than N-body units. The main bottleneck, however, is the fact that so few codes (so far) include binary evolution. This is one reason why progress on the interface with binary evolution (Section 4.1) is viewed as being so urgent.

5.5. Comparisons for the future

While the above examples concentrate on cluster-like problems, another stellar dynamics problem of growing importance is the evolution of galactic nuclei. There is a need for comparable but more

appropriate initial conditions (perhaps including 1 or 2 black holes).

One of the weaknesses of current modelling is the fact that all codes used for studying dense stellar systems incorporate the same fitting formulae for stellar evolution (Hurley et al., 2000). This is one aspect that cannot be validated empirically.

There is a considerable need for comparative studies using the different codes now available for binary star evolution. These tend, of course, to be based on similar assumptions, and so consistent results need not imply that the results are entirely trustworthy, but it would be interesting to know just how great the differences can be.

It should soon be possible to incorporate 'live' SPH codes into dynamical models. To test this aspect, and to compare SPH simulations with other hydrodynamical codes or approximate methods, a few initial conditions for stellar collisions should be devised.

At present no code incorporates 'live' stellar evolution. When this improves, it will be useful to specify collision products to feed to the stellar evolution codes (say, one blue straggler progenitor and one collisionally stripped giant).

Further developments, as they occur, will be added to the web page of WG7.

6. The future

The MODEST collaboration will continue to have bi-yearly meetings, and the schedule for the next few MODEST meetings were outlined, as follows:

- MODEST-3, Melbourne, Australia, 9–11 July 2003, hosted by Rosemary Mardling
- MODEST-4, Lausanne, Switzerland, 12–14 January 2004, hosted by Georges Meylan
- MODEST-5, Hamilton, Ontario, Canada, 11–14 August 2004, hosted by Alison Sills
- MODEST-6, Heidelburg, Germany, 17–19 January 2005, hosted by Rainer Spurzem
- MODEST-7, Evanston, Illinois, USA, 29–31 August 2005, hosted by Fred Rasio

One outcome of MODEST-2 was the creation of eight 'working groups', designed to focus the interests of the different members of the collaboration; and to allow all members of the community to find what they need more quickly and easily. The working groups, listed below, all have websites that can be reached from the main MODEST website.

Working group	Contact person	email address
1. Star formation	Ralf Klessen	rklessen@aip.de
2. Stellar evolution	Onno Pols	o.r.pols@astro.uu.nl
3. Stellar dynamics	Ranier Spurzem	spurzem@ari.uni-heidelberg.de
4. Stellar collisions	Marc Freitag	freitag@ari.uni-heidelberg.de
5. Simulating observations of simulations	Simon Portegies Zwart	spz@science.uva.nl
6. Data structures	Peter Teuben	teuben@astro.umd.edu
7. Validation	Douglas Heggie	d.c.heggie@ed.ac.uk
8. Literature	Melvyn Davies	mbd@astro.le.ac.uk

7. Summary

The second meeting of the MODEST collaboration, devoted to MOdelling DEnse STellar systems, was held in December 2002 at the University of Amsterdam, Holland. This paper provides a summary of the meeting, including the presentations made, the discussions held, and the conclusions drawn. There was a clear consensus among the participants that the MODEST approach is reasonable, useful and clearly necessary for many problems in stellar astrophysics, and is not confined simply to globular cluster dynamics, but spans many scales from star formation in turbulent molecular clouds to the dynamics of galactic nuclei.

The main improvement to the state of models since MODEST-1 was the expansion of the 'toy model' for interfacing stellar evolution, stellar dynamics and hydrodynamics into a simple working codes called TRIPTYCH and TRIPLETYCH. The expansion of the MODEST collaboration from one based in N-body stellar dynamics to one that encompasses many different dynamical methods (Monte Carlo, gaseous and hybrid) is an improvement to the collaboration, in that the validity of results can be tested more easily through comparison of standard cases simulated by many groups.

The main science goals outlined at MODEST-2 involved understanding the initial conditions for star cluster formation. The interaction between stars and gas, primordial mass segregation, and the effects of pre-main sequence stars all need to be considered. In addition, we need to follow the observations closely. Observations of massive star formation or blue stragglers and binaries in the field provide crucial information for both initial conditions and later evolution of clusters.

The main theoretical and modelling goals included creating standard interfaces for the different physics modules (particularly binary evolution) that are needed for this work, so that we can test the different versions by swapping different implementations in and out of the codes. The effects of triple and higher order star systems (both primordial and dynamically created) is becoming more and more necessary to understand and include as the dynamics simulations become more complicated. We outlined a list of 'complicated cases' in Section 4.3—these are scenarios that we see in the dynamics simulations for which we do not have a good theoretical understanding. Similarly, there is a need for detailed stellar evolution calculations of non-standard stars (collision products, binary merger products, etc.), which can form the basis of the recipes or on-the-fly stellar evolution calculations.

While we have made significant progress in the short existence of this collaboration, there is still much work to be done, and we hope that future workshops in this series will continue the congenial atmosphere that characterized the first two MODEST workshops. We hope to see you and continue the discussion at MODEST-3!

Acknowledgements

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