Dynamical Evolution of Dense Stellar Systems
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Dancing with Black Holes

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Abstract. In this talk, I will describe my efforts over the last six years to implement regularization methods suitable for studying one or more interacting black holes by direct N-body simulations. Three different methods have been adapted to large-N systems: (i) Time-Transformed Leapfrog, (ii) Wheel-Spoke, and (iii) Algorithmic Regularization. These methods have been tried out with some success on GRAPE-type computers. Special emphasis has also been devoted to including post-Newtonian terms, with application to moderately massive black holes in stellar clusters.

Evolution of Compact Binaries in Globular Clusters

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Abstract. We discuss the evolution of compact-binary populations of Globular Clusters (GC) due to dynamical formation, destruction and encounter with surrounding stars – in particular that of the X-ray binary (XB) populations. We consider the compact binary population distribution $n(a,t)$ as a continuous function of binary radius a and time t and compute its evolution in a GC core with density ρ_c, radius r_c and velocity dispersion v_c. We consider dynamical formation and destruction due to tidal capture, exchange and ionisation in a continuous approximation to the stochastic nature of these processes. Evolution of a binary is determined by hardening due to encounter with surrounding stars (collisional hardening), gravitational radiation, magnetic braking, and mass transfer after Roche-lobe contact. We compute the total number of XBs formed as a function of two GC parameters, namely, $\Gamma \equiv \rho_c^2 r_c^3/v_c$ and $\gamma \equiv \rho_c/v_c$, which are measures of the two-body encounter rate and the binary-single-star encounter rate respectively. We find agreement with observations of Galactic GC XB populations. Our computations also predict a roughly uniform binary-period distribution of GC XB population. We argue that the essential causes for this period distribution are the characteristics of mass transfer following Roche-lobe contact, by showing that roughly the same binary-period distribution is obtained when we follow the evolution after "turning off" the terms representing stellar encounters in a dense GC core.

Infant Mortality: causes, timescales, and implications

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Abstract. Studies of galactic and extra-galactic cluster systems have shown that the majority of clusters formed do not survive past a few 10s of Myr. This process, which has been dubbed 'infant mortality', appears to be largely independent of mass and the likely culprit is the rapid removal of residual gas left over from the star-formation process. This rapid gas removal which destroys the majority of clusters leaves its imprint on the age distribution of clusters and field stars, the profile of the cluster, and the internal dynamics of the cluster. I will present a series of recent studies which quantify this effect and show that this phase cannot last longer than a few 10s of Myr, despite recent claims in the literature which suggests that infant mortality can last upwards of a few Gyr. Some implications of this process will also be discussed.

The influence of gas expulsion on the evolution of star clusters and cluster systems

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Abstract. We have performed a large set of N-body simulations studying the effect of residual-gas expulsion on the survival rate and final properties of star clusters. In our simulations, we have varied the star formation efficiency, gas expulsion timescale and strength of the external tidal field, obtaining a three-dimensional grid of models which can be used to predict the evolution of individual star clusters or whole star cluster systems by interpolating between our runs.

Our simulations show that most star clusters will not survive residual gas expulsion and that the cluster sizes, bound mass fraction and final velocity profiles of the surviving clusters are all strongly influenced by the details of the gas expulsion. When applied to the globular cluster system of the Milky Way, our results show that it is possible to turn an initial power-law profile of cluster masses into a log-normal one by gas expulsion and the subsequent destruction of low-mass clusters alone. In this case, the log-normal mass profile of the cluster system is already established within a few 10s of Myrs. Observations of star cluster systems in merging and interacting galaxies might therefore help to confirm or reject our scenario.

Black hole motion as catalyst of orbital resonances

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Abstract. The motion of a black hole about the centre of gravity of the host galaxy induces a strong response from the surrounding stellar population. We treat the case of a harmonic poten tial analytically and show that half of the stars on circular orbits in that potential shift to orbits of lower energy, while the other half receive a boost and therefore recede to a larger radius. The black hole acts as a catalyst of evolution of the stellar energy distribution function $f(E)$ but remains itself on an orbit of fixed amplitude. We show that this effect is operative out to a radius of ≈ 1 to 2 times the hole's influence radius, R_{bh}. We use numerical integration to explore more fully the response of a stellar distribution to black hole motion. We consider orbits in a logarithmic potential and compare the response of stars on circular orbits, to the situation of a 'warm' and 'hot' (isotropic) stellar velocity field. While features seen in density maps are now wiped out, the kinematic signature of black hole motion still imprints the stellar line-of-sight mean velocity to a magnitude $\simeq 18\%$ the local root mean-square velocity dispersion σ.

Effects of stellar collisions on star cluster evolution and core collapse

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Abstract. It is well known from previous studies that primordial binary interactions and star-star collisions can significantly modify the dynamical evolution of dense star clusters. We systematically study the effects of collisions on the overall dynamical evolution of dense star clusters using Monte Carlo simulations over many relaxation times. We derive many observable properties of these clusters, including their core radii and the radial distribution of collision products. We also study different aspects of collisions in a cluster taking into account the shorter lifetimes of more massive stars, which has not been studied in detail before. Depending on the lifetimes of the significantly more massive collision products, observable properties of the cluster can be modified qualitatively; for example, even without binaries, core collapse can sometimes be avoided simply because of stellar collisions.

Star formation in ultra-dense clusters and the creation of massive stars

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Abstract. What are the highest stellar densities achieved during cluster formation? High stellar densities at birth can lead to a number of potentially observable phenomena such as the generation of dynamical runaways and may even produce conditions that lead to the creation of massive stars by collisions.

I try to answer this question both from direct observation of embedded clusters and from dynamical modeling of slightly older (10 Myr old) systems. I also consider the theoretical limit expected for the density of a cluster core which shrinks adiabatically due to the accretion of inflowing gas, and show that the predicted limit (wherein the maximum core density exceeds the mean cluster density by the square of the total number of stars in the cluster) is well reproduced by existing calculations.

Science Highlights from the ACS Virgo and Fornax Cluster Surveys

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Abstract. The ACS Virgo and Fornax Cluster Surveys are HST/ACS programs to obtain deep, high-resolution imaging in the F475W (g) and F850LP (z) filters for 143 early-type members of the Virgo and Fornax clusters, the two galaxy clusters nearest to the Milky Way. The sample galaxies span a range of more than 500 in blue luminosity, from giants to dwarfs. In this talk, I shall summarize science highlights from the two surveys, paying particular attention to the properties of galactic nuclei and extragalactic star clusters.

Multiple stellar populations in Globular Clusters: collection of info from the Horizontal Branch

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Abstract.

There is now mounting evidence that Globular Cluster (GC) stars were not formed in a single burst of star formation, even if it is not clear which are the progenitors of the population of helium rich, oxygen poor and nitrogen rich stars which are found in most GCs so far examined. In this work we summarize the information on the "second stellar generation" which comes out from the interpretation of the horizontal branch (HB) population of several GCs in terms of varying helium content of their stars. The sample examined so far has wildly different HB morphologies (mostly red HB, mostly blue HB, HB containing a populous sample of RR Lyr variables) but in all of them we can infer the presence of an important helium rich population, and probably, of a gap in the helium content between the "standard helium" population and its minimum value in the helium rich population. We examine the very interesting case of the GC M3, in which the distribution of periods of RR Lyr, together with the assumption of the existence of a helium rich population, severely constraints the mass loss on the red giant branch, contrary to common assumptions made so far.

Why haven't loose globular clusters collapsed yet?

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Abstract.

We report on the discovery of a surprising observed correlation between the slope of the low-mass stellar global mass function (GMF) of globular clusters (GCs) and their central concentration parameter $c = \log(r_t/r_c)$, i.e. the logarithmic ratio of tidal and core radii. This result is based on the analysis of a sample of twenty Galactic GCs with solid GMF measurements from deep HST or VLT data. All the high-concentration clusters in the sample have a steep GMF, most likely reflecting their initial mass function (IMF). Conversely, low-concentration clusters tend to have a flatter GMF implying that they have lost many stars via evaporation or tidal stripping. No GCs are found with a flat GMF and high central concentration. This finding appears counter-intuitive, since the same two-body relaxation mechanism that causes stars to evaporate and the cluster to eventually dissolve should also lead to higher central density and possibly core-collapse. Therefore, more concentrated clusters should have lost proportionately more stars and have a shallower GMF than low concentration clusters, contrary to what is observed. It is possible that severely depleted GCs have also undergone core collapse and have already recovered a normal radial density profile. It is, however, more likely that GCs with a flat GMF have a much denser and smaller core than suggested by their surface brightness profile and may well be undergoing collapse at present. In either case, we may have so far seriously underestimated the number of post core-collapse clusters and many may be lurking in the Milky Way.

Problems in the Evolution of Binary Stars

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Abstract.

The evolution of single stars in a cluster can be reasonably well modeled with a pre-constructed grid of evolutionary runs. However binaries are harder, because (a) there are more input parameters to define a binary, and (b) the physics regarding their evolution is less certain. This seems to suggest that an N-body code will need to connect directly to a binary-star evolution code.

One of the least certain areas of close-binary evolution is contact binaries. These are not common, but they are not rare either. I shall explore the consequences of certain assumptions regarding the evolutionary progress of contact binaries.

A UNIFIED PICTURE OF THE LIFECYCLES OF STAR CLUSTERS

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Abstract. We present a unified picture of the lifecycles of star clusters, beginning with their formation in dense molecular clouds in the interstellar medium and ending with their dissolution in the the general field-star population. This picture was developed through a combination of detailed observations of clusters systems, particularly those in the Solar neighborhood and in the interacting Antennae galaxies, along with several theoretical studies, in collaboration with Rupali Chandar, Brad Whitmore, and Qing Zhang. This picture turns out to be remarkably simple, although undoubtedly approximate. By a few simple formulae, it accounts for most, if not all, the main statistical properties of star cluster systems (formation rates, mass functions, age distributions, etc). These formulae embody and clarify the physical processes involved in the formation and evolution of cluster systems, although there are still a few unresolved theoretical issues. Our recent unpublished work indicates that this picture applies to clusters of many different types (open, populous, globular) in galaxies of many different types (large, small,

interacting, quiescent, etc)–hence our claim that it is likely to be "universal." Since most, if not all, stars form in clusters of some sort, this unified picture of star clusters probably also provides much of the framework for a unified picture of stellar populations in galaxies.

Blue Straggler Stars in Galactic Globular clusters: tracing the effect of dynamics on stellar evolution

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Abstract. The ultra-dense cores of Globular Clusters (GCs) are very efficient "furnaces" for generating exotic objects, such as low-mass X-ray binaries, cataclysmic variables, millisecond pulsars, blue stragglers, etc. Most of these stars are thought to be the product of the evolution of binary systems, possibly originated and/or hardened by stellar interactions. Thus, the nature and even the existence of these exotic objects can be strongly affected by the cluster core dynamics, and their study can serve as powerful diagnostic of the dynamical evolution of GCs. This talk I review the main properties of Blue Stragglers Stars (BSS) in galactic GCs. A flower of results on the BSS frequency, radial distribution, and chemical composition are presented and discussed. Recent results on the measured frequency of binaries in the core of a number of clusters are also presented.

Dynamical evolution of rotating globular clusters with embedded black holes

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Abstract. Evolution of self-gravitating rotating dense stellar systems (e.g. globular clusters) with embedded black holes is investigated. The interplay between velocity diffusion due to relaxation and black hole star accretion is followed together with cluster differential rotation using 2D+1 Fokker Planck numerical methods. The models can reproduce the Bahcall-Wolf $f \propto E^{1/4}$ ($\rho \propto r^{-7/4}$) cusp inside the zone of influence of the black hole. Angular momentum transport and star accretion processes support the development of central rotation in relaxation time scales, before re-expansion and cluster dissolution, latter due to mass loss in the tidal field of a parent galaxy. Gravogyro and gravothermal instabilities conduce the system to a faster evolution leading to shorter collapse times with respect to models without black hole.

Binary Stars and Globular Cluster Dynamics

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Abstract. I will review recent work on the interplay between binary star evolution and dynamical interactions in globular clusters, based on both N-body and Monte Carlo simulations. In particular, I will discuss our current theoretical understanding of "binary burning" and how dynamical interactions of primordial binaries determine the structural parameters of globular clusters.

Fully Self-consistent N-body Simulation of Star Clusters in the Galactic Center

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Abstract.

In order to follow the evolution of a star cluster in the Galactic center, we developed an N-body code which can handle the long-term dynamical evolution of star clusters in their parent galaxy. In our code, both a star cluster and its parent galaxy are modeled by N-body systems. The star cluster is integrated by an Hermite integrator with direct force calculation and the galaxy and the interaction between the galaxy and the cluster by a leapfrog integrator with tree force calculation. As far as we know, ours is the first of such codes in the world.

Using this code, we investigated the orbital evolution of a star cluster inspiraling to the Galactic Center. The central region of the Galaxy contains very young and massive stars. Inspiraling of young and compact clusters is a possible explanation of the origin of these stars.

We found that the inspiral timescale of the star cluster is significantly shorter than that obtained by previous works where the dynamical friction was calculated analytically. Our result implies that the timescale problem of the inspiral scenario was not so severe as previously suggested.

Furthermore, our model can explain the structures of the Galactic center such as the stellar disk which contains stars in highly eccentric orbits and assemblies of young stars such as IRS 13E. Stars which have eccentric orbits can be understood as having escaped from a star cluster with an eccentric orbit and IRS 13E may be the remnant of a star cluster containing an intermediate-mass black hole.

Test of the accuracy of approximate methods to handle distant binary-single star encounters

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Abstract. In the numerical simulations of evolution of star clusters, binary-single star interactions frequently take place. Since the direct integration of them is time consuming, distant interactions between binaries and field stars are often integrated by using some approximations. Traditionally the effect of the error caused by the approximated treatment is regarded as small enough to be ignored. However, if we have a binary-dominated core, the enegy drift would be large. In order to evaluate the effect of this neglect of the weak perturbation from distant single particles, we perform numerical experiments of integration using higher order and accuracy method. The result will be reported.

Observational Evidence for Black Holes in Globular Clusters

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Abstract. There have been many observational claims for the existence of intermediate mass black holes, many of which have been challenged with alternative interpretations. The existence of intermediate mass black holes, however, has important consequences for understanding how supermassive black holes acquire their mass. Furthermore, whether or not these black holes exist in globular clusters has important implications for the cluster itself and for estimating their number density. I will review the current observational evidence for black holes in clusters, including dynamical studies with both radial velocities and proper motions.

How does the environment of star clusters determine their evolution?

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Abstract. The first few Gyrs of the evolution of star clusters is determined by several internal and external effects that lead to the disruption of a large fraction. The time-scale of dissolution and how this may or may not depend on cluster mass has been under debate recently. We present evidence from observations of the age distribution of clusters in the Small Magellanic Cloud (SMC), the solar neighbourhood and M51 that the life time of star clusters that have survived the gas removal phase (first 10 Myr) strongly depends on the (galactic) environment in which they evolve. These observations can be explained well by the results of N-body. The main environmental parameters are the strength of the tidal field and the presence of (giant) molecular clouds. Both effects result in cluster disruption time scales that depend in the same way on cluster mass, in agreement with the observations. We show some examples of how incompleteness effects in the observations, in particular biases towards clusters with young ages, affect the age distribution and can lead to the fallacious interpretation of rapid (mass independent) cluster disruption. As a particular case we discuss the clusters in the SMC, for which it was claimed recently that they dissolve similarly during the first Gyr as the clusters in the Antennae galaxies. We show that this interpretation is caused by incompleteness effects. When taking these into account, we find that star clusters in the SMC in fact live very long (several Gyrs), in good agreement with what is expected from the tidal field strength of the SMC.

Monte Carlo simulations of star clusters with primordial binaries. Comparison with N-body simulations and observations.

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Abstract. We have performed a large set of Monte Carlo simulations of tidally limited star clusters containing a large fraction of primordial binaries. Stellar evolution of single stars was followed by the algorithm of Hurley et al. (2000) and internal evolution of binary stars by the methods of Hurley et al. (2002). The results of Monte Carlo simulations have been compared with N-body simulations available in the literature and others specially run for the purpose of this comparison. The main aim of this work was to calibrate the Monte Code code, in particular to find the best values of parameters which hold for as many different numbers of object in the system as possible. The chosen parameters were then used in simulations of the evolution of the old open cluster M67, a cluster which has been studied thoroughly in the literature with N-body techniques. We describe in particular those aspects of the evolution of the global cluster structure, and the binary, white dwarf and blue straggler

populations, which can be most easily compared with the observations (though not all channels for blue straggler formation are represented yet in our simulations).

Dynamical Evolution of Globular Clusters in Hierarchical Cosmology

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Abstract.

We test the hypothesis that globular clusters form in supergiant molecular clouds within high-redshift galaxies. Numerical simulations demonstrate that such large, dense, and cold gas clouds assemble naturally in current hierarchical models of galaxy formation. These clouds are enriched with heavy elements from earlier stars and could produce star clusters in a similar way to nearby molecular clouds. The masses and sizes of the model clusters are in excellent agreement with the observations of young massive clusters. Do these model clusters evolve into globular clusters that we see in our and external galaxies? In order to study their dynamical evolution, we calculate the orbits of model clusters using the outputs of the cosmological simulation of a Milky Way-sized galaxy. We find that at present the orbits are isotropic in the inner 50 kpc of the Galaxy and preferentially radial at larger distances. All clusters located outside 10 kpc from the center formed in the now-disrupted satellite galaxies. The spatial distribution of model clusters is spheroidal, with a power-law density profile consistent with observations. The combination of two-body scattering, tidal shocks, and stellar evolution results in the evolution of the cluster mass function from an initial power law to the observed log-normal distribution. However, not all initial conditions and not all evolution scenarios are consistent with the observed mass function.

The Star Cluster Systems of Local Group Galaxies

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Abstract. The Local Group hosts a wide variety of different star cluster systems in different environments. Already the globular cluster systems of the Milky Way and of M31 exhibit a number of differing properties in terms of overall census, ages, metallicities, kinematics, and structural parameters. Dwarf galaxies tend to have less concentrated and more elliptical globular clusters (if they contain any at all). The highest globular cluster specific frequencies are found in the least massive, least luminous galaxies – the dwarf spheroidal galaxies. For nearby dwarfs the globular clusters turn out to be as old as the oldest Galactic globulars. Some of the Local Group dwarfs contain nuclear star clusters. Galaxies like the Magellanic Clouds and M31 have continued to form populous star clusters throughout their entire life time, a behavior not found in other Local Group galaxies where the epoch of globular cluster formation ended within a few Gyr after the Big Bang. In these cases, the preferred subsequent mode of star formation has been the formation of (usually short-lived) open clusters and OB associations. The properties of these populous clusters as well as their inferred survival times in different environments are being discussed, along with those of open clusters.

Giant Elliptical Galaxies: Globular Clusters and UCDs

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Abstract. The huge globular cluster populations found in giant E galaxies allow us to explore numerous emerging trends and correlations at higher confidence than can be done in smaller galaxies. Some of the most intriguing of these include, (a) the global shape of the Fundamental Plane, (b) the structural connection between the most luminous globular clusters and the new class of Ultra-Compact dwarfs (are UCDs the same thing as supermassive

GCs?), and (c) the mass-metallicity relation affecting the blue, metal-poor GC sequence. What is its origin? This paper gives an overview and current prospects for studying these correlations from within the nearby giant E galaxies.

Modelling Individual Globular Star Clusters

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Abstract.

Astronomers have constructed models of globular clusters for over 100 years. These models mainly fall into two categories: (i) static models, such as King's model and its variants, and (ii) evolutionary models. Most attention has been given to static models, which are used to estimate mass-to-light ratios and mass segregation, and to combine data from proper motions and radial velocities. Evolutionary models have been developed for a few objects using the gaseous model, the Fokker-Planck model, Monte Carlo models and N-body models. These models have had a significant role in the search for massive black holes in globular clusters.

In this presentation the problems associated with these various techniques will be summarised, and then we shall describe new work with Giersz's Monte Carlo code, which has been enhanced recently to include the stellar evolution of single and binary stars. We describe in particular recent attempts to model the nearby globular cluster M4, including predictions on the spatial distribution of binary stars and their period distribution, to illustrate the effects of about 12 Gyr of dynamical evolution. We also discuss an approximate way of predicting the "initial" conditions for such modelling.

N-body Models of Open Clusters

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Abstract. In this talk I will discuss recent results arising from N-body models ranging in size from $N = 2\,000 - 100\,000$ bodies. Along the way I will touch on subjects such as the morphology of clusters in the Large Magellanic Cloud, the origin of planetary systems such as our Solar System, and the evolution of binaries in star clusters. I will discuss limitations of the models, such as simplified initial conditions, and how these will be addressed in the near future.

Virtual Laboratories and Virtual Worlds

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Abstract. Since we cannot put stars in a laboratorium, astrophysicists had to wait till the invention of computers before becoming laboratory scientists. For half a century now, we have been conducting experiments in our virtual laboratories. However, we ourselves have remained behind the keyboard, with the screen of the monitor separating us from the world we are simulating. Recently, 3D online technology, developed first for games but now deployed in virtual worlds like Second Life, is beginning to make it possible for astrophysicists to enter their virtual labs themselves, in virtual form as avatars. This has several advantages, from new possibilities to explore the results of the simulations to a shared presence in a virtual lab with remote collaborators on different continents. I will report my experiences with the use of Qwaq Forums, a virtual world developed by a new company (see http://www.qwaq.com).

Neutron Stars in Globular Clusters

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Abstract.

In dense star clusters, dynamical interactions lead to the frequent formation of many exotic sources, unusual binaries and systems of higher multiplicity. This is particularly important for the formation of X-ray binaries and millisecond pulsars. As only a very small fraction of neutron stars formed in clusters are retained, this study inevitably becomes a "million-body problem" that requires the use of specialized numerical tools.

I will discuss how neutron stars are produced and retained in globular clusters, outlining the most important dynamical channels and evolutionary phases that affect the population of mass-transferring binaries with neutron stars and result in the formation of recycled pulsars. Another question to be discussed is whether we can put constraints on binary stellar evolution by comparing the observed millisecond pulsar populations in 47 Tuc and Terzan 5 with theoretical results.

The Simple Principles That Underlie the Dynamics of Globular Clusters

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Abstract. In this era of simulation it is easy to forget how simple the dynamics of globular clusters is. First, Jeans' theorem combines with Poisson's equation to give a unique correspondence between any isotropic velocity distribution and the spatial density profile of the cluster. The velocity distribution is controlled by relaxation, which brings it as close to Gaussian as it can get. Relaxation is described by the Fokker-Planck equation, whose steady-state solution is well approximated by a Gaussian, reduced by a constant that brings it down to zero at the escape velocity that the Galactic tidal field imposes. Except for scale factors, clusters differ only in central concentration, which controls how deeply the escape velocity cuts into the velocity distribution.

The dynamical equilibrium of a cluster is especially stable for two reasons. First, if the velocity distribution is the steady-state solution of the Fokker-Planck equation at one radius, it is equally so at all radii. Second, as the local relaxation time lengthens with increasing radius, the fraction of stars that escape per relaxation time goes up in a way that almost exactly compensates, so as to keep the density distribution in balance as stars escape.

The foregoing applies to stars of a single mass, whereas a real cluster has a mass function. To a good approximation, equipartition of energy applies, and more massive stars are more concentrated to the center — especially binaries and massive remnants.

Anisotropy adds little complication, as it is observed to be small.

Formation of Stellar Clusters

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Abstract. Stars form by gravoturbulent fragmentation of interstellar gas clouds. The supersonic turbulence ubiquitously observed in Galactic molecular gas generates strong density fluctuations with gravity taking over in the densest and most massive regions. Collapse sets in to build up stars and star clusters.

Turbulence plays a dual role. Or global scales it provides support, while at the same time it can promote local collapse. Stellar birth is thus intimately linked to the dynamical behavior of parental gas cloud, which determines when and where protostellar cores form, and how they contract and grow in mass via accretion from the surrounding cloud material to build up stars. Slow, inefficient, isolated star formation is a hallmark of turbulent support, whereas fast, efficient, clustered star formation occurs in its absence.

I will review the current progress in star formation theory and discuss results from numerical calculations of gravoturbulent cloud fragmentation. Special emphasis lies on the complex dynamical evolution of nascent star clusters, on the mass growth history of individual protostars, and on the resulting mass spectrum of stars, the IMF.

Ultraviolet Spectroscopy of Stellar Exotica in 47 Tucanae

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Abstract. I will present far-ultraviolet spectroscopy of ≃50 exotic and/or evolved objects in the core of 47 Tucanae. The data was obtained with STIS onboard HST in slitless mode, which is possible because crowding is manageable in the far-UV, even in the cluster core. I will discuss the key results and discoveries emerging from this spectroscopic survey, including (i) the spectroscopic confirmation of several suspected cataclysmic variables; (ii) an absence of emission lines from other CV candidates and objects on the white dwarf sequence (thus indicating that these are not interacting binaries); (iii) a binary system that appears to contain a 'stripped" secondary star; (iv) a blue straggler exhibiting a very strong far-UV excess (perhaps due to a WD companion); (v) evidence that the brightest blue straggler may be a fast rotator.

The formation and disruption of star clusters, and implications thereof for galactic astrophysics

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Abstract. Star clusters appear to form in very dense configurations with radii near 1 pc independent of mass for $M < 10^6 M_\odot$. The stellar population within a cluster also appears to be formed in an organised manner, starting with the least massive stars, such that a well-defined correlation exists between the mass of the most massive star and the cluster mass. This is most probably a result of stellar feedback on the cluster-forming nebula. Observations suggest that the star-formation efficiency is typically less than about 40 per cent. If the residual gas is driven out on a crossing time or faster, then the cluster unbinds dramatically, it "pops". Such "popping" clusters may contribute relatively hot kinematical populations to galactic fields.Above about $10^6 M_\odot$ the "clusters" appear to become more complex, by being composite populations or cluster complexes. Massive versions of such complexes may evolve to ultra-compact dwarf galaxies through the merging of the individual clusters on a time-scale of about 100Myr.

Clues to Globular Cluster Evolution from Multiwavelength Observations of Extragalactic Systems

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Abstract.

We present a study of the globular cluster systems of nearby elliptical and S0 galaxies at a variety of wavelengths from the X-ray to the infrared. Our analysis shows that roughly half of the low mass X-ray binaries, that are luminous tracers of accreting neutron star or black hole systems, are in globular clusters. The particularly efficient low mass X-ray binary formation rate in globular clusters is not surprising due to dynamical interactions, especially in the core. However, our observations reveal a variety of expected and unexpected correlations between low mass X-ray binaries and various physical characteristics of globular clusters such as mass, metallicity, age, and half-light radius. We present the implications of this study on the formation and evolution of both globular clusters and low mass X-ray binaries. In particular, the surprising correlation of the low mass X-ray binary formation rate with metallicity provides a unique insight into the metallicity structure of extragalactic cluster systems. We weigh the theoretical models that attempt to explain the metallicity effect. We also comment on the implications of our observations on neutron star kick velocities, the presence of black holes in globular clusters, and the effect of galaxy environment on globular cluster formation and evolution.

Observations and simulations of the Blue Straggler Star radial distributions: clues on the formation mechanisms

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Abstract. By means of high-resolution and wide-field observations in the UV and optical bands we have derived the radial distribution of the Blue Stragglers Star (BSS) population in a number of galactic globular clusters. Monte-Carlo dynamical simulations have then been used to interpret the observed radial distributions in terms of the percentage of collisional and mass-transfer BSS populating each cluster. I will present the main results thus obtained and an overall comparison from cluster to cluster for the whole sample collected so far, mainly focussing on the clues about the BSS formation mechanisms that such an approach is able to provide.

Where the Blue Stragglers Roam: The Link Between Formation and Environment

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Abstract. Current observational evidence seems to indicate that blue stragglers are a dynamically created population, though exactly how the mechanism(s) of formation operates remains a mystery. We search for links between blue straggler formation and environment by considering only those stars found within one core radius of the cluster center. In so doing, we aim to isolate a sample that is representative of an approximately uniform cluster environment where, ideally, a single blue straggler formation mechanism is predominantly operating. Relative blue straggler frequencies are found and apart from new anticorrelations with the central velocity dispersion and the half-mass relaxation time, we find no other statistically significant trends.

A simple, semi-analytic model designed to reproduce the observed trends in the core is also presented. We find that the majority of the blue stragglers created are the products of mass transfer in tight, low-mass binary systems. Our results suggest that the binary fraction could be a crucial parameter in shaping blue straggler populations.

Better and more abundant observations of binary systems and their numbers could therefore prove an important step in better understanding blue straggler formation.

An X-ray emitting globular cluster black hole

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Abstract.

I will discuss the recent discovery of strong variaiblity from an ultraluminous X-ray source in a spectroscopically confirmed globular cluster in NGC 4472. These data are the strongest evidence to date for a black hole in a globular cluster, overcoming all previous major objections - such a bright X-ray source can be only a black hole, since the variaibility requires that it be a single source, while the spectroscopic identification of the cluster makes it clear that the optical counterpart is not simply an active galactic nucleus with colors in the globular cluster locus. I will go on to discuss the implications of this discovery and the points for and against an intermediate mass black hole nature of the accretor.

The effect of stellar-mass black holes on the structural evolution of globular clusters

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Abstract. We present the results of direct ($N = 10^5$), realistic N-body modelling of globular clusters in the Magellanic Clouds, aimed at investigating a dynamical origin for the radius-age trend observed in these systems. We find that stellar-mass black holes, formed in the supernova explosions of the most massive cluster stars, constitute a dynamically important population. These objects rapidly form a dense core where interactions are common, resulting in the scattering of black holes into the cluster halo, and the ejection of black holes from the cluster. These processes heat the stellar component, resulting in prolonged core expansion of a magnitude matching the observations. Less massive remnants, such as neutron stars, cannot alone produce the required expansion. Significant core evolution is also observed in Magellanic Cloud clusters at very early times. We find that this does not result from the action of black holes, but can be reproduced by the effects of mass-loss due to rapid stellar evolution in a primordially mass segregated cluster. The possibility of large-scale core expansion over an extended duration has important implications for much globular cluster work, particularly that involving cluster survivability.

Current status of GRAPE project

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Abstract. In this talk, I'll summarize the current status of GRAPE project. GRAPE-6, completed in 2002, has been used by a number of people, for a wide variety of problems such as planet formation, star cluster dynamics, galactic nuclei, and cosmology. In 2004, we started the development of the next-generation machine, GRAPE-DR. GRAPE-DR has a architecture radically different from that of previous GRAPEs, in that it does not have hardwired pipeline for gravitational force calculation but a large number of small and simple programmable

processors. This change make it possible to apply GRAPE-DR to a wide range of problems to which GRAPE was not efficient, and at the same time it helps us to explore new algorithms for N-body simulations. The GRAPE-DR chip was completed in 2006, and second prototype board was completed in May 2007. We hope to have full production-level board commercially available by the end of year 2007. A single board will offer the theoretical peak speed of 2 Tflops, about 20 times as that of a single PCI card version of GRAPE-6.

Hybrid Direct/Tree Code for Modeling Star Clusters in a Strong, Time-Dependent Tidal Field

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Abstract. Accurately modeling the evolution of a star cluster in a strong tidal field poses unique computational challenges. We present a hybrid code that combines the strengths of two different approaches to computing gravitational forces. The internal, collisional, dynamics of the cluster is followed with a direct N-body integrator, Kira, while the galactic tidal field is modeled with a cosmological code, GADGET, that uses a tree to evaluate gravitational forces in $O(NlogN)$ time. The quadrupole moment at the center of mass of the cluster is used to compute the external potential and provides a mechanism for mass loss. This forms a robust, bidirectional interaction. The advantages of combining two highly-developed and well-established software packages at such high level are obvious and many; not the least of these is the ability to include other physical processes, e.g., stellar evolution.

One problem to which we applied this technique is the evolution of a dense star cluster near the Galactic center. We are also using this code to explore the effects of the strong time variation in the tidal field of merging galaxies on the evolution of young star clusters forming during the merger.

Resonance, Chaos and Stability in the General Three-Body Problem

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Abstract. Three-body instability is fundamental to astrophysical processes on all length and mass scales, from construction of planets to construction of massive elliptical galaxies. Thus it is vital that we have a thorough understanding of this classic problem, both from the mathematical point of view as well as the physical. While substantial progress has been made in understanding so-called *Hill* stability, that is, stability against close approach for systems with small mass ratios, very little has been made for the more general *Lagrange* stability, that is stability against escape of one of the bodies. The one exception is the work of Wisdom (1980) who considered the planar circular restricted three-body problem with small mass ratio. The key idea in Wisdom's work is that of *resonance overlap*, a concept used in the study of chaos in conservative systems.

Most of what we know about (Lagrange) stability in the general three-body problem has been gleaned from direct numerical integrations. I will present a simple analytical stability criterion which uses the resonance overlap concept. It has *no free parameters*, and makes no assumptions about the mass ratios or orbital elements. It reveals the dependence of stability on all the parameters of the system, providing insight not afforded by numerical treatments as well as a practical algorithm for use in planetary and stellar N-body simulations.

Binary Star Populations of Open Clusters. Benchmarks at the Interface of Stellar Dynamics and Stellar Evolution Theory

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Abstract. Current capabilities of N-body calculations permit detailed simulations of rich open clusters with primordial binary populations over ages of several Gyr. The evolution of the binary populations, and the concurrent production of stellar products that cannot be explained by standard single-star evolution theory, represent critical benchmarks - and in some cases, predictions - of the interplay of stellar dynamical and stellar evolutionary theories.

For the past decade, the WIYN Open Cluster Study has been defining in detail the stellar populations of five rich open clusters spanning ages from 150 Myr to 7 Gyr. In particular, the Wisconsin group has obtained nearly 30,000 radial-velocity measurements of nearly 6000 stars in these clusters, and has identified over 900 binaries with orbital periods of less than 10,000 days (i.e., hard binaries), of which nearly 400 have yielded orbit solutions. I will present the hard binary populations in these clusters. I will also discuss particular case studies of binaries and encounter products that provide insights into dynamical evolution processes.

Internal Structures of Globular Clusters and the Fundamental Plane

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Abstract. The high spatial resolution of HST has allowed the measurement of detailed internal surface-brightness profiles for globular and other massive star clusters in many galaxies beyond our own. We have now derived and/or analysed the spatial structures of nearly 350 well-resolved globular clusters in 6 galaxies including the Milky Way. I will summarise our recent work to fit these data with a variety of simple physical models, including critical comparisons to the standard King lowered-isothermal spheres. We have combined the results of this fitting with a basic population-synthesis analysis, to derive a full suite of structural and dynamical parameters for all of these clusters. This homogeneous database is ideally suited for defining and exploring the fundamental plane of globular clusters, making inter-galaxy comparisons and contrasting with the fundamental planes of massive young clusters, galaxy nuclei, and even elliptical galaxies. I will review some of our efforts in this direction as well, and discuss the clues that are emerging about the formation and dynamical histories of globulars.

A Dynamical Origin for Early Mass segregation in Young Star Clusters

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Abstract. Some young star clusters show a degree of mass segregation that is inconsistent with the effects of standard two-body relaxation from an initially unsegregated system without substructure and in virial equilibrium. We present the results of a survey of N-body simulations exploring the evolution of initially clumpy clusters. Our simulations show that mergers of small clumps that are initially mass segregated, or in which mass segregation can be produced by two-body relaxation before they merge, generically lead to larger systems that inherit the progenitor clumps' segregation. We conclude that clusters formed in this way are naturally mass segregated, accounting for the anomalous observations and suggesting that this process of prompt mass segregation due to initial clumping should be taken into account in models of cluster formation and dynamics.

A Brief History of Regularisation

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Abstract. The various methods for regularisation of the gravitational few-body problem, from the coordinate transformation by the Kustaanheimo-Stiefel method to the more recent methods of algorithmic regularisation, are reviewed. Numerical comparisons of the performance of the methods are presented and future research suggested.

6th and 8th order Hermite Integrator using Snap and Crackle

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Abstract.

The 4th order Hermite integrator can be naturally extended to higher orders by using higher order derivatives of acceleration calculated directly. We derived 6th and 8th order schemes, which use derivatives up to the second order (snap) and up to third order (crackle), respectively. These higher order schemes can be combined with individual timestep algorithm. We implemented an N-body time integration program with these high-order individual time step algorithms. The additional cost of the direct calculation of higher order terms are not excessive. The floating-point operation counts per interaction of the 4th, 6th and 8th order scheme are 60, 96 and 144, respectively in our implementation.

To calculate the contribution of one particle j to snap or crackle of particle i, we need acceleration and jerk for both of particles i and j at the time of particle i. With higher order predictor, we can construct predictors of the required order for acceleration and jerk. So we do not need to calculate the acceleration and jerk for all particles to calculate snap and crackle for particle i, and the time integration algorithm is essentially the same as that for the traditional 4th order scheme.

We have done a series of numerical experiments. The result suggests that the 6th order integrator allows larger mean step size compared to that of the 4th order integrator by a factor $2 \sim 3$, in a typical required accuracy in simulations of dense stellar systems. For higher accuracy, the difference can be much larger.

Central Dynamics of Globular Clusters: the Case for a black hole in ω Centauri

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Abstract. Globular clusters have been classified into two groups due to their dynamical state. They are considered to be either pre-core-collapse or post-core-collapse systems. Clusters are classified as post-core-collapse when they show concentrated surface brightness profiles, with a steep central cusp; while pre-core collapse clusters are less concentrated and have flat central cores. I briefly review recent results from models and observations, which show that the assumption of bimodality might not give the complete picture of central dynamics in globular clusters. Some of the observations can be explained by the presence of a single or a binary intermediate mass black hole in the center of the clusters. As an example, I present a central surface brightness profile from an ACS image, as well as central velocity dispersion measurements from GEMINI-GMOS that suggest the presence of an intermediate mass black hole of $4 \times 10^4\ M_\odot$ in the center of ω Centauri.

The Origin of the Universal Globular Cluster Mass Function

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Abstract.
Evidence favouring an initial globular cluster mass function similar to that observed today has accumulated over recent years. This implies that the observed universal Gaussian globular cluster mass function is the preserved imprint of the cluster formation process. I investigate how the shape of the initial globular cluster mass function is affected by expulsion from the protocluster of the leftover star forming gas due to supernova activity. Owing to the corresponding weakening of its gravitational potential, the protocluster retains a fraction only of its newly formed stars. The initial mass of a star cluster thus depends on gas removal, which is worth being put to the test as a possible controlling mechanism of the initial cluster mass function shape. I show that an approximately Gaussian initial cluster mass function with the observed width and turnover may be the imprint of the gas removal phase, provided that the protoglobular clouds have a characteristic mass of about $10^6\ M_\odot$. The universality of the globular cluster mass function may therefore originate from a common value among galaxies for the protoglobular cloud mass-scale. The distribution function of masses of protoglobular clouds (e.g. truncated power-law or Gaussian) influences only weakly the shape of the resulting initial globular cluster mass function. The gas removal process and the protoglobular cloud characteristic mass dominate the relevant physics. Moreover, gas removal is highlighted as the likely prime cause of the predominance of field stars in the Galactic halo.

Observational Evidence of Multiple Stellar Populations in Globular Clusters

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Abstract. Recent photometric investigations, based on HST high accuracy photometry, have shown that the color magnitude diagram of Galactic globular clusters is much more complex than once thought. The presence of multiple main sequences, multiple sub-giant branches, coupled with multimodal horizontal branches are clearly challenging the paradigm that globular clusters host simple stellar populations, and call for new ideas on star formation processes in star clusters.

We will present the available photometric and spectroscopic observational facts. We will show that multiple star formation episodhes must differ from cluster to clusters. The increasing evidence of multiple populations in globular clusters rises changelling questions both for the cluster dynamical evolution, and for the evolution of their stars.

Millisecond Pulsars in Globular Clusters

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Abstract. There are currently more than 130 known pulsars in the Galactic globular cluster system, and almost half of these have been discovered using the Green Bank Telescope (GBT) within the past 5 years. The vast majority of these systems are millisecond pulsars and just over half of them are members of binaries. The rich cluster Terzan 5 alone now contains 33 known millisecond pulsars, by far the most of any globular cluster. Many of the pulsars are truly unique and/or exotic objects that could only have been produced in dense cluster cores after stellar interactions. Some of the stranger systems that have been recently uncovered include the fastest known spinning neutron star (PSR J1748−2446ad at 716 Hz), 10 highly eccentric binary systems, and 4−5 millisecond pulsars which seemingly have main-sequence-like stellar companions. Several of the pulsars constrain the equation of state of matter at supra-nuclear densities, while others will eventually provide masses of spun-up neutron stars

and interesting tests of gravitational theories. In addition, the pulsars will allow us to probe a wide variety of other astrophysics such as eclipse mechanisms, cluster dynamics, and the structure of the interstellar medium.

Masses and M/L ratios of bright globular clusters in NGC 5128

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Abstract. We present an analysis of the radial velocities and velocity dispersions for 27 bright globular clusters in the nearby elliptical galaxy NGC 5128 (Centaurus A). For 22 clusters we combine our new velocity dispersion measurements with the information on the structural parameters, either from the literature when available or from our own data, in order to derive the cluster masses and mass-to-light (M/L) ratios. The masses range from 1.2×10^5 M$_\odot$, typical of Galactic globular clusters, to 1.4×10^7 M$_\odot$, similar to more massive dwarf globular transition objects (DGTOs) or ultra compact dwarfs (UCDs) and to nuclei of nucleated dE galaxies. The average M/L_V is 3 ± 1, larger than the average M/L_V of globular clusters in the Local Group galaxies.

The correlations of structural parameters, velocity dispersion, masses and M/L_V for the bright globular clusters extend the properties established for the most massive Local Group clusters towards those characteristic of dwarf elliptical galaxy nuclei and DGTOs/UCDs. The detection of the mass-radius and the mass-M/L_V relations for the globular clusters with masses greater than $\sim 2 \times 10^6$ M$_\odot$ provides the link between "normal" old globular clusters, young massive clusters, and evolved massive objects.

A Near-infrared Survey of the Rosette Complex: Clues of Early Cluster Evolution

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Abstract. The majority of stars in our galaxy are born in embedded clusters, which can be considered the fundamental units of star formation. We have recently surveyed the star forming content of the Rosette Complex using FLAMINGOS in order to investigate the properties of its embedded clusters. In this talk we will discuss the results of our near-infrared imaging survey. In particular, we will focus on the first evidence for the early evolution and expansion of the embedded clusters. In addition we will present data suggesting a temporal sequence of cluster formation across the cloud and discuss the influence of the HII region on the star forming history of the Rosette.

Changing structures in Galactic star clusters

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Abstract. We investigate the structures of embedded and open clusters using statistical methods, in particular the normalised mean correlation length, the mean edge length of the minimum spanning tree and the combined parameter Q (Cartwright & Whitworth 2004, MNRAS, 348, 589), which permits to quantify the cluster structure, and also to identify previously unknown clusters. While the structure of embedded clusters holds clues to their formation mechanism, the structure of open clusters reflects their dynamical evolution. Star clusters build up from several subclusters evolving from a structured to a more centrally concentrated stage. The evolution is not only a function of time, but also of the mass of the objects. Massive stars are usually centrally concentrated, while lower-mass stars are more widespread, reflecting the effect of mass segregation. Using this method we find

that in IC 348 and the Orion Nebula Cluster the spatial distribution of brown dwarfs does not follow the central clustering of stars at all, giving important clues to their formation mechanism by supporting the ejected embryo scenario.

The Formation and Dynamics of the SMC Cluster NGC 346

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Abstract. Young resolved clusters in the SMC provide us with the opportunity to study the details of their formation and the efficiency of feedback mechanisms at low metallicity. HST/ACS images reveal that the young cluster NGC 346 is composed of a number of subclusters, and the region as a whole is surrounded by complex gas structures, indicating a clear interaction with the environment. To probe the dynamics of the subclusters and the ionized gas, we have obtained high resolution optical spectroscopy for a number of slit positions across the region. Surprisingly, we find little evidence of gas motions in the ionized gas. This suggests that, at the low SMC metallicity, the cluster O star winds are not powerful enough to sweep away the residual gas. Instead, we find that stellar radiation is the dominant process shaping the interstellar environment. We use HST photometry of the stellar population to derive the star formation history of the region. We find large numbers of pre-main sequence stars and derive an age of 3 ± 1 Myr for the main central cluster. Within the uncertainties, the subclusters appear to be coeval with each other and the formation of the main cluster. By coupling these results with the dynamics of the subclusters, we are able to derive the actual formation and assembly history of NGC 346. We compare our findings to the most recent models of hierarchical molecular cloud fragmentation and cluster formation.

Post-Newtonian Dynamics in Dense Stellar Systems

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Abstract. Dense stellar systems (star clusters and galactic nuclei) are some of the most promising sources of gravitational waves since black holes may form and grow in them. In the talk I will describe how relativistic dynamics is included in N-body simulations of such systems, and discuss examples how we model sources in different wavelength regimes, showing results from triple and binary black holes in galactic nuclei, and giving an outlook to projected work for star clusters. Also I'll explain how these theoretical activities are embedded into collaborative programs with gravitational wave observatories, such as the VESF (Virgo-EGO science collaboration) and the German LISA cooperation.

Effects of Hardness of Primordial Binaries on Evolution of Star Clusters

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Abstract. We performed N-body simulations of star clusters with primordial binaries using a new code, GORILLA. It is based on Makino and Aarseth (1992)'s integration scheme on GRAPE, and includes a special treatment for relatively isolated binaries. Using the new code, we investigated effects of hardness of primordial binaries on whole evolution of the clusters. We simulated four $N = 16384$ equal-mass clusters containing 10 % (in mass) primordial binaries whose binding energies are $1, 10, 100$, and $1000kT$, respectively. Additionally, we also

simulated a cluster without primordial binary and that in which all binaries are replaced by stars with double mass, as references of soft and hard limits, respectively. We found that, in both soft ($\leqslant 1kT$) and hard ($\geqslant 1000kT$) limits, clusters experiences deep core collapse and shows gravothermal oscillations. On the other hands, in the intermediate hardness ($10 - 100kT$), the core collapses halt halfway due an energy releases of the primordial binaries. The core radii at the halt can be explained by their energy budget.

Dynamical Evolution of Star Clusters with Primordial Binaries and Intermediate Mass Black Holes

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Abstract.

The evolution of a star cluster is strongly influenced by the presence of primordial binaries and of a central black hole, as dynamical interactions within the core prevents a deep core collapse under these conditions. We will present the results from a large set of direct N-body simulations of star clusters that include an intermediate mass black hole (IMBH), single and binary stars. We will highlight the structural and dynamical differences for the various cases showing in particular that on a timescale of a few relaxation times the density profile of the star cluster does no longer depend on the details of the initial conditions but only on the efficiency of the energy generation due to gravitational encounters at the center of the system. The dense cores of these systems are natural laboratories for stellar dynamics and frequent multiple interactions lead to the formation of hierarchical systems that we use to predict the abundance of triples stars in globular clusters, in particular with one member of the triple being a pulsar.

The Imprints of IMBHs on the Structure of Globular Clusters: Monte-Carlo Simulations

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Abstract.

While the presence of intermediate mass black holes (IMBHs) in the center of globular clusters has been predicted more than 30 years ago, it was not until recently that observations could, through the detection of velocity and density cusps in the cluster cores, provide direct indications for their existence. However, for an unambiguous confirmation extensive modelling of the cluster evolution is required. We present results of a series of Monte-Carlo simulations investigating the imprints of a central black hole on the core structure of globular clusters. We investigate the core radius and velocity dispersion profile of the inner cluster regions as a function of the stellar mass spectrum and the total number of stars, ranging from 10^5 up to a few 10^6, taking into account physical stellar collisions, stellar evolution as well as strong binary interactions. We compare our results to observations, putting new constraints on the masses of potential black holes in the centers of globular clusters, as well as to other simulations published previously in the literature. The Monte-Carlo technique gives us the advantage to model the evolution of globular clusters with a realistic number of stars, which is important to ensure the correct rate of the different dynamical processes at work that all scale differently with N.

The Problem of Three Stars

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Abstract. The Problem of Three Stars is similar to the Classical Three-Body Problem, but the approach is different from the usual mathematical discussion. For example, the finite size of the stars has to be taken into account in dense stellar environments. In addition, problems like three-body scattering are central to the three-star problem, but have not been studied much in other contexts. Here the classical work by Heggie (1975) is the foundation of much of the current activity. I will discuss the three-body scattering as an example of rather complete phase space mixing. Also the stability of hierarchical triple stars is reviewed.

A simultaneous Chandra/HST survey of the compact binaries in the globular cluster 47 Tuc: optical results

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Abstract. Globular clusters are important laboratories to study stellar and binary evolution, and the role therein of dynamical encounters. In high-resolution Chandra X-ray images of globular clusters dozens of interacting binaries have been discovered, including exotic systems containing white dwarfs and neutron stars. Optical identification, although challenging, is the first step towards learning more about their properties and how these may differ from the field population. With the aim of obtaining a complete census of its compact binaries, we have undertaken a deep survey of simultaneous HST/ACS and Chandra observations of the globular cluster 47 Tuc, which contains by far the largest numbers of identified compact binaries of any globular cluster. These data include the first deep images of 47 Tuc in Hα, which is a powerful probe of ongoing accretion. We present new identifications and source classifications, including the discovery of a counterpart of a candidate quiescent neutron-star low-mass X-ray binary. We also find optical variability of up to 3.5 mags in the 11-day time span of our data in 5 cataclysmic variables (CVs) that is likely related to variations in the mass accretion rate. We show the simultaneous X-ray/optical behavior and discuss our results in the light of previous suggestions that the CVs in globular clusters are dominated by magnetic systems and have lower accretion rates when compared to field systems. First results of an archival study to search for more large-amplitude variations of the CVs in 47 Tuc are also presented.

X-ray sources in globular clusters

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Abstract. All stars emit X-rays, but some emit more than others... The increased sensitivity and position accuracy of the Chandra satellite has opened the study of faint X-ray sources in the clusters of the Milky Way, and of bright X-ray sources in globular clusters of other galaxies. By comparing clusters with different properties, i.e. mass, central density, metallicity, we can establish how the number of X-ray sources in them – c.q. the probability of them to contain a source – depends on these properties; and we can do this for each class of source separately.

I will discuss the observations, dependances, and possible explanations.

Dynamical Evolution of Mass-segregated Clusters

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Abstract. We present the results of N-body simulations exploring the early and long-term dynamical evolution of initially mass-segregated star clusters. The implications of early mass segregation on the evolution of the clusters structure, lifetime and stellar content are discussed.

Observational Constraints on the Formation and Evolution of Globular Cluster Systems

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Abstract. I will discuss the observational properties of globular cluster systems, with a particularly emphasis on how these inform and constrain theoretical studies of the formation and dynamical evolution of globular clusters. The talk will both highlight new observational results and connect these to previous work. I will note several successful examples of the interplay between theory and observation in the area of dynamical evolution of globular cluster systems, and will discuss several key open questions.
