Panel Discussion on Observing Simulations and Simulating Observations

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Abstract. N-body simulations of star cluster evolution have reached a high degree of realism, by incorporating more and more elements of stellar dynamics, stellar evolution, and hydrodynamics. At the end of this conference, six participants discussed how to present the increasingly realistic data from star cluster simulations in a way that is most useful for a direct comparison with observations.

1. Introduction, by Piet Hut

Only after organizing this panel did I realize that the acronym of the title, OSSO, has the meaning of 'bone' in Italian – perhaps fitting for a conference in the American Museum of Natural History, which is generally associated with paleontology. Also, until recently, star cluster simulations have been rather skeletal in that they have left out much of the essential physics, including stellar evolution. Only recently have we begun to put flesh and skin on the bones of our simulations, as we have seen during the conference.

Two stumbling blocks have prevented a production of realistic simulations. The first one is related to a lack of hardware speed. Although Fokker-Planck and gas models have provided important insight into the dynamics of star clusters, they are not well suited for studying the dynamical effects of a significant binary population. Therefore, direct $N$-body simulations are called for. On a typical workstation, with a speed of order

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of a Gflops, one can now run a thousand-body run overnight, and with more patience a 5,000-body run can be performed if one is willing to wait a month or more. To model the richest open clusters, with 50,000 stars, a Tflops speed is called for, and modeling a typical globular cluster, with at least 500,000 stars, requires a Pflops speed. In 1995, the Tflops barrier was broken with the GRAPE-4, and the GRAPE-6 is expected to reach a speed of 100 Tflops in 2001. Finally, the GRAPE-8 is expected to deliver several Pflops well before the end of the decade, thus allowing the modeling of any globular cluster.

However, with hardware solutions being just around the corner, software limitations are making themselves felt all over the place—much like everywhere else in the world nowadays. For one thing, what is desperately needed is access to simple stellar evolution codes that are robust enough to serve as modules in star cluster simulation codes. It would be ideal to construct models of blue stragglers on the fly, immediately after they form in a collision, and then follow their specific evolution, without having to interpolate between tracks based on the very different evolution that starts with zero-age main sequence stars. It seems to be a well-kept secret that after almost a half century of numerical stellar evolution work, still no code can follow the full evolution of a single star without human intervention, something that is impractical once we are dealing with hundreds of thousands of stars.

Other software challenges involve the visualization of the Tbytes that are currently generated with our Tflops computations, and the Pbytes that will be generated towards the end of the decade. Constructing simulation archives, with efficient ways to interrogate the data and to pipe relevant data subsets to other geographical locations, are tasks that we are only beginning to confront. And in order to make contact with the observations, the most direct way will be to simulate observations of the simulations—a software S.O.S. reaction to the coming data flood.

2. Observing Simulations, by Adrienne Cool

Simon, Piet, Steve, and Jun have taken the initiative to try to bridge the gap that sometimes exists between observers and theorists working on star clusters. This is a very welcome development, since while we may not always like to admit it, it can be surprisingly hard to find solid points of contact. Questions as apparently trivial as “what is the core radius of this cluster?” turn out, as became clear at the workshop, to involve numerous subtleties that often get swept under the rug.

It’s time to improve this situation. What with the rapid advances in the theoretical modeling of clusters, and the richness of the observational data being collected almost daily, increasingly direct and meaningful comparisons between theory and observation are beginning to be possible.
So how to begin to bridge the gap? The approach that Simon and collaborators have taken involves “observing simulations.” They are collecting the results of their cluster simulations, generating from them simulated observations, and offering these up to observers for analysis. The ways in which this sort of approach can be useful are just beginning to be explored. One obvious utility is to see how closely what you get out resembles what you put in. How accurately is the main-sequence luminosity function, the main sequence binary fraction, or the white dwarf cooling sequence reproduced? Do the core radius and tidal radius extracted from the simulated data set match the core radius and tidal radius of the simulated star cluster from whence it came?

To some extent, questions like this can be (and have been) addressed by widely used “artificial star tests.” One complication, as any observer will instantly point out, is that how much you can extract from the data will depend sensitively on its nature and quality. What you choose to simulate by way of filters, pixel size, psf structure, cosmic rays, artifacts (the list goes on and on) will all have an impact on the results. Exploring such questions could be interesting from the point of view of using simulations to test the feasibility of various kinds of measurements, but is perhaps beside the point here. In the present context, the more important opportunity that this next generation of artificial star tests affords is to find out whether observers and theorists are even speaking the same language. In some cases (core radius is a good example) we already know that we aren’t. Communicating through simulated observations can provide the impetus to find a common language.

Perhaps even more interesting is to consider how to take advantage of what is really new: the fact that there is a fully 3-dimensional cluster to work with. This means you can “observe” the cluster from an arbitrary point in space. In principle, you could also observe the cluster at a variety of equivalent (or not) points in time. Thus, comparisons can be made between results obtained by observing the very same cluster from different places or times. Beyond the inherent appeal of even the imagined freedom to move about in space and time, this approach could help address questions related to small number statistics, and provide the means to explore potentially subtle projection effects.

Taking this a step further, Mike Shara has challenged us all to think about what can be learned not just from analyzing simulated observations of a cluster frozen at a particular moment in time, but with rendered 3-dimensional dynamic simulations, like the one we all got a taste of at the opening reception. This kind of viewing can be done in real time, in the sense that one can make choices about where to move and what to look at on the fly (so to speak). Opportunities to observe simulations in this way could this be a boost to developing intuition about cluster dynamics. Observing simulations and discussing them in small groups
could also provide an intriguing new forum for enhancing communication between theorists and observers.

3. Defining Definitions, by Charles Bailyn

There is often confusion regarding the meaning of a number of commonly used terms relating to the dynamics of clusters. Observers and theorists use these terms without defining them, and in ways which make it difficult to compare theoretical and observational results. In some cases it is not clear what the appropriate definition ought to be. We feel it is important for all workers to provide careful definitions when they use these terms, and to make an effort to record results in ways that are not merely clear, but useful to the widest possible audience.

The chief offender seems to be "core radius". This is a well-defined parameter of a King model, but it is not clear how it should be defined in situations in which a King model cannot be fit, either because the data are not extensive enough or because the distribution is poorly fit by a King model. It is often assumed that \( r_c \) represents a distance at which the density falls to half the central density. (Note that the conversion of density to projected density is a continuing difficulty in comparing observations of real clusters and observations of simulations — it is MUCH better to project models into observational space, so cluster simulators are strongly encouraged to quote projected densities). But this definition of \( r_c \) begs the question of how a central value of the density is defined, either observationally or theoretically. Not only is a "central" density an instrumentally defined term for observers, but it is undefined theoretically too, due to the stochastic nature of the inner regions of clusters.

One suggestion would be to define a ratio of radii, and a ratio of encircled densities, and scale the radii until the density ratio is correct. The density within the inner radius might then provide a robust measure of the "central" density, while the outer radius would define a "core radius". But it is not clear what the appropriate ratios would be, or even whether such a definition would in fact be robust, stable, or repeatable. Clearly, further investigation is required to create appropriate definitions for observers of simulated or real data.

Other terms which create confusion include "collapsed core", "tidal radius", "half-mass radius" and "primordial binary". A collapsed core is generally considered to be one whose density rises continuously to the center. But the problems of defining central density arise here in particularly virulent form. It is notable that the core of 47 Tuc, perhaps the best studied globular cluster, is sometimes described as collapsed, and sometimes not. Tidal radius is another term which is well-defined in the context of a King model, but it is not synonymous with the largest distance a cluster member can be from the cluster center. This difference is crucial to remember when computing or observing the half-mass radius, since poten-
tially significant cluster members can lie beyond the tidal radius. Finally, there was general agreement that primordial binaries refer to binaries in which the two component were bound at the start of the cluster lifetime, even if the parameters of the binary orbit have been significantly altered by subsequent dynamical interactions.

4. Simulation Bottlenecks, by Steve McMillan

The impending appearance of GRAPE-6 will significantly lower the main computational barrier to direct $N$-body simulations of star clusters and dense stellar systems. From a purely computational standpoint at least, with existing software and a reasonably fast host, we can say loosely that GRAPE-4 enables the study of many, but not all, open clusters, while GRAPE-6 will allow us to perform simulations of all open clusters and at least the smaller globulars. It then becomes feasible to contemplate “throughput” experiments, in which one systematically varies the assumed cluster initial conditions and compares the results directly with real systems observed today. However, the old adage “garbage in, garbage out” continues to apply. The sources of “garbage” in this case are uncertainties in (i) the initial models ($t = 0$), (ii) evolutionary processes ($0 < t < \text{now}$), and (iii) interpretation of observations ($t = \text{now}$).

The initial state of a cluster is not well known. Perhaps the most important uncertainty, from both the dynamical and the observational standpoint, stems from the properties of the primordial binary population: numbers, masses, mass ratios, and periods. It is standard practice to assume an initially homogeneous sample (i.e. no initial mass segregation), but there seems no particular reason to suppose that this is really the case, and in fact there are arguments to suggest the opposite—that more massive stars and binaries will form preferentially in the denser central regions. Finally, the question of what exactly is meant by “$t = 0$” is also unresolved. Low-mass stars may take hundreds of millions or even billions of years to reach the main sequence and, at the time of formation, may have radii hundreds of times greater than typically assumed in the models. Whether or not this significantly affects cluster evolution remains to be seen, but it at least highlights the fact that very substantial uncertainties exist in the initial models.

There are many open questions concerning the essential physics. The proper treatment of binary and stellar evolution is critical if we wish to interpret cluster observations in the light of model simulations. While stellar evolution theory is sufficiently advanced that the evolution of most stars can be modeled by interpolation between standard tracks, even here there are areas of uncertainty. Specifically, the evolutionary tracks of high-mass stars, and especially merger products, remain poorly determined. The largest uncertainties are again associated with binaries, and some phases of binary evolution are currently modeled in a very heuristic fashion. In par-
ticular, the lifetimes of contact binaries and their descendents are largely unknown.

Finally, there are questions concerning the interpretation of observations. Excellent cluster data are now becoming available, both for open clusters (e.g. the WIYN Open Cluster Survey) and for globulars (with high-precision HST and Chandra studies now commonplace). However, much data analysis still involves the use of unrealistically simple dynamical templates. Obvious examples are the use of multi-mass King models, or dynamical models that neglect binaries, stellar evolution, and/or the influence of Galactic tides, as standards against which observations are gauged. For the foreseeable future, the preferred approach to making the comparisons will be to project the simulations into the observational plane, using simulated telescope, filter, and detector characteristics as appropriate, with extra field stars and obscuration if desired, and to “observe” these model systems using the same techniques as would be applied to real clusters.

5. Mergers in the Universe, by Mario Livio

I like to look at collisions from a more global point of view. For example, we know from the Medium Deep Survey, and from the two Hubble Deep Fields, that the fraction of faint galaxies with irregular morphologies increases with redshift. Many of these are suggestive of merging or colliding systems. Similarly, there is evidence for galaxies being physically smaller in size beyond redshift $z=1$. All of these observational facts can be interpreted in terms of hierarchical galaxy formation – in the high redshift universe we are seeing the “building blocks” of today’s galaxies.

A related question is that of the formation of clusters in galaxy collisions. For example in the "Antennae" (NGC 4038/4039) merging galaxies, HST has detected between 800 and 8000 luminous young clusters that formed in the collision process. The luminosity function of these clusters is (to first order) a power law, with an exponent of $-2.1$. It would be interesting to see whether theoretical simulations can reproduce such a power law.

Another question concerns the central supermassive black holes in galaxies. Such black holes appear now to reside at the center of essentially all galaxies (and their mass is correlated with the velocity dispersion). One of the issues in active galactic nuclei is whether these black holes grow mainly by accretion or through mergers. The hierarchical galaxy formation picture may suggest that mergers should be an important growth mechanism.

All of the above suggest that collisions are not only important for the fate of individual stars, but also more globally.
The computational power and astrophysical brain power being brought to bear today on the structure, evolution and populations of dense star clusters is nothing short of exhilarating. There is some danger, however, that we are becoming victims of our own success with problems analogous to those being faced by observational astronomers: data floods of epic proportions.

Observing the simulations is an ever increasing challenge in a (soon-to-be) Petabyte world. I predict that we will need more and more collaboration from our computer scientist colleagues, and novel display devices (like the Hayden Planetarium digital dome) to let our eyes and brains pick out the data diamonds from the numerical gravel. The astrophysics department at the American Museum of Natural History has committed a significant amount of digital dome night time (equivalent to ground based telescope dark time) to attacking the visualization problem. Ongoing collaborations of star cluster simulators (particularly GRAPE aficionados), computer scientists and Planetarium visualization experts are aimed at producing a 30 meter "digital telescope" in the heart of Manhattan, long before CELT or OWL come on line.

My cheers and challenges are directed at those intrepid theorist/numericist astrophysicists who try to simulate observations of dense star clusters. A poster child for this difficult endeavour is the gutsy paper of Di Stefano and Rappaport (ApJ 423, 274 (1994)) who boldly predicted the existence of about 100 cataclysmic variables in each of Omega Cen and 47 Tuc. Hubble Space Telescope surveys in narrowband Halpha and for erupting dwarf novae have found a few cataclysmics in several clusters surveyed so far, but nothing like the 100 predicted. Much more sensitive Hubble and Chandra observations now in hand may yet turn the tide. My point, though, is that SPECIFIC predictions of the numbers and types of unusual stellar species in clusters are rare, but EXTREMELY valuable as tempting carrots to observers. Rarer still are those simulations marrying stellar populations models with realistic dynamics.

An important goal of the coming generation of GRAPE-6 simulations (coupled to evolution/population codes) should be specific predictions of the numbers, observational characteristics and spatial distributions of cataclysmic binaries, millisecond pulsars, neutron stars and red giants in many of the globular clusters of the Milky Way. This will help observers push for larger allocations of telescope time (particularly on HST and Chandra) to produce tougher constraints, driving simulators to more sophisticated predictions. The populous star clusters of the Magellanic Clouds should not be ignored in this effort, as HST and Chandra can detect some of their stellar exotica . . . and the simulated observations can suggest how these clusters differ from those of our Milky Way.