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Panel Discussion

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Abstract. Four panelists gave their reports. Three of them are complied here. Additional comments are included in the report by the moderator Sugimoto.

1. Sugimoto on General Accounts

Sugimoto as moderator chaired Panel Discussion. After introductory report by Sugimoto, three panelists gave their reports. Main topics were 1) general accounts, 2) cosmology, 3) galaxies, and 4) globular clusters. Three of them are compiled in this proceeding. Discussions after each report were too diverse to include here. This implies that subjects of this Symposium still have wide front to explore.

Characteristics of Self-Gravity : Gravitational interaction has special characteristics as compared with other interactions. The first is that its effective range is infinity. If we express it symbolically in the form of Yukawa-type potential $V \sim \exp(-r/\lambda)/r$, the range λ is *infinity.* The second is that there is not repulsion but attraction. In this respect, the gravitational force is unique: Coulomb force has also the same $\lambda = \infty$, but its effective range becomes *effectively finite* because of Debye-type shielding in a system without net charges.

The second characteristics makes a system confined in a finite size L. Because of infinite λ, the system size L is *always* smaller than λ. In this sense any astronomical system, however large, is always a *micro* system in the sense that the self-energy due to the interaction plays the most important role.

Since the self-energy is proportional to the square of the number of elements (or the mass) consisting of the system, it is not an extensive quantity any more. In standard thermodynamics, it is tacitly assumed that energies are extensive (proportional to the mass M of the system). Of course, we know the case of energy of surface tension that is proportional to $M^{2/3}$ (*sub*-extensive), but the case of self-gravity is proportional to M^2. This *super-extensive* nature brings about *thermodynamic instability*, which is tacitly assumed as not the case in the standard thermodynamics. This is the reason why some important behaviors of the system become *out of common sense of standard thermodynamics.* Examples are *negative specific heat* and *non-existence of entropy maximum*, etc.

Beyond Descartes and Laplace : The infinite λ brings also about coherence all over the system, and over subsystems, if any, of different sizes. In addition, the infinite λ implies that there is no characteristic length of the system. Therefore, the similarities may prevail among astronomical objects and phenomena of different scales, and at the same time, the system may show fractal structures.

The coherence over the whole region of the system implies that the system is typically *non-linear* even in its fundamental structure itself. At the same time, the finite volume of the system due to the gravitational attraction makes the system *open* to the outer space. Therefore, any astronomical system is a typical *non-linear, open system.*

Though we have beautiful mathematics and methodology to treat *linear systems* or *linearized systems* by means of perturbation method, *non-linear systems* can only be treated case by case. Nevertheless, in the natural world (and also in society), non-linear systems under strong coupling and systems *out of equilibrium* by *finite amplitude* (thus non-linear) are rather common. They may be main subjects of science in the 21-th century and we badly need to promote our understanding on them. Among them, astronomical systems allow, though numerically in most cases, quantitative treatment because of the simplest yet typical functional form for the long-range interaction.

Descates' method was such that a system may be divided into elements, that the nature of the element is investigated separately, and that the whole system may be understood by integrating behaviors of the elements. It has greatly helped opening and promoting the age of modern science and technology, where the *causes* and the *results* are well separable. However, there are many non-linear systems where they are not separable any more, and their existence and behaviors should be understood by grasping the system as a whole.

Such discussion reminds us of Laplace's daemon (intelligence) who can make N-body type calculation however large. Nowadays, we can do it at a scale by means of ultra-fast computer. One of the main objections to it is the existence of *chaos.* Actually, a great number of three-body problems that yields the chaos are embedded in the N-body type calculation. However, we have to notice the followings. It is this existence of chaos in a Hamiltonian system that brings about global thermodynamic properties of the system, and N-body calculation of colliding galaxies, for instance, yields meaningful and unique results on merging of galaxies etc. *despite* the chaos. The chaos brings about divergence in Γ ($6N$ dimensional) space, but unique results on *global* distribution of stars in 3-dimensional configuration space.

Virtual Observatory : Thus we have to consider how we can promote such understanding of non-linear systems. Numerical studies will play one of the most important roles. In this relation *virtual observatory* was proposed and discussed in this Symposium. It will have a large computer accessible from any place in the world, and will integrate softwares for simulation and toolkits for analysis and visualization. Its role will be two-fold; one is for simulating real astronomical objects or phenomena, and the other is for doing *numerical experiments*.

Real observatories equipped with telescopes of different wavelengths explore astronomical objects and phenomena as they are at present. On the other hand the *virtual nature* of the virtual observatory makes it possible to solve for evolution of the system by including the time-axis of any scale. At the same time, it can make numerical *experiments* by deleting, exaggerating, or deforming physical processes occurring in nature. Such experiments are indispensable to reach extracting and understanding of essential accounts in non-linear behavior of the systems.

In my opinion, we went a little too far to simulate or, in other words, tried to reproduce extant objects and phenomena too much in detail that are nowadays observed with very advanced real observatories. It may make us apt to overlook essential processes working therein. In order to understand not only the object-by-object but also fundamental non-linear reasoning underlying therein, more numerical experiments are necessary and referees of journals should not reject related papers just saying that it is unrealistic. Because of wider parameter space some numerical experiments often require more computer power than reproducing realistic models by tuning parameters. However, we have enough computational power nowadays.

2. Athanassoula on Galaxies

The recent increase in computer power has allowed major advances in many astronomical subjects, as demonstrated beyond doubt in this symposium. Yet a lot remains to be done. In particular in the field of galactic dynamics there are many challenges for state-of-the-art simulations. The problem of galactic haloes is a good example. Since dark matter can not be directly observed, we rely on its effects on other galactic components in order to derive its properties. High quality simulations of specific dynamical processes in isolated or interacting galaxies with haloes of different shape or radial profile should set constraints on the vast available parameter space. Thus we can set constraints on the shape of haloes by modelling the formation and the properties of bars or warps. The understanding of the role of resonance in the dynamical evolution of galaxies, both in isolation and during interactions (cf. Weinberg, this volume; Athanassoula, this volume) is a further challenge to which state-of-the-art N-body simulations can make a substantial contribution. High quality simulations of groups and clusters of galaxies are necessary in order to understand the evolution of galaxies in such environments (cf. Dubinski, this volume), but also the segregation by morphological type found observationally, or the formation of dwarf galaxies and globular clusters by interactions and their survival in the group/cluster environment. The richness and the central concentration of the group, as well as its dark matter distribution, will influence the results, so that a large number of simulations are necessary for such studies. Accretion of small satellites is both common and crucial in determining the evolution of bigger galaxies, within which they can form substructures. Nevertheless, fully self-consistent simulations of such events imply state-of-the-art simulations with large particle numbers, since they involve modelling galaxies of very different masses. Last but not least an increase in computer power will allow us to make our simulations more realistic. Hence an effort is necessary in order to include properly in computer codes one or more gas components and their interactions, star formation, stellar evolution and other phenomena which influence the dynamical evolution of a galactic system.

I would like here to underline the important role that GRAPE systems have played in galactic dynamics. They offer a high CPU performance at an affordable price. They are particularly well suited for small research groups and/or groups not having sufficiently good access to big supercomputer centers. Furthermore, they allow a very flexible planning of computer work, which is difficult to establish in supercomputing centers. Thus a bright new idea can be tested out immediately, rather than having to wade through the usual channels of application for CPU time, with their inherent refereeing delays. All of us small groups using GRAPEs are deeply indebted to the Tokyo group – headed initially by D. Sugimoto and now by J. Makino – that has developed them.

Let me now end with a few words about virtual observatories, or rather about their computer equivalents. Supercomputer centers, like big telescopes, are expensive – both in their building and in their running – and thus every effort should be made for an optimum use. More often than not simulations made in order to answer a particular astrophysical problem may yield important information on other problems as well. For example a simulation of cluster evolution, made in order to study the formation of brighter cluster members, can also be used for studies of galaxy interactions in a cluster environment, or of the formation and evolution of galactic debris. Similarly N-body simulations of bar formation and evolution can provide realistic potentials, useful for orbital structure calculations. The group which made these simulations may not wish to tackle all the problems on which its simulations may shed light, and thus sharing them with other groups will ensure a better use of the data. Sharing state-of-the-art simulations will also minimise duplication of effort. It will help groups not having access to big computer centers, particularly in developing countries. The improvements in network communication will make the access to the data easier.

There is nevertheless a crucial difference between virtual observatories and their computer analogues. Any observational data collected, even with a small telescope, is in principle useful, sometimes even after higher quality observations of the same object become later available. As an example let me mention the plates or spectra which allowed the identification of the supernovae precursors. Thus a spectrum of the precursor of SN1987A had been observed by a group in our observatory, and the corresponding plate was duly reanalysed after the supernova went off. On the other hand simulations are based on ideas or theories, and, if these are later found to be wrong, the simulations become of limited or of no use. This is true even if better simulations of the same problem are carried out. Therefore the computer analogues of virtual observatories should be more flexible and need to cover only a rather limited time span. Finally such structures should be international, particularly if they are to help developing countries. Clearly the IAU has a role to play here.

3. Heggie on Globular Clusters

3.1. Introduction

In these remarks I would like to stand back a bit from the details of the symposium papers, and take a slightly more general look at where we stand in the use of N-body simulations in the study of star clusters. I would also have liked to say something about the excellent contributions and reviews we have heard on problems of planet formation and star formation, which I found very interesting, but have grossly insufficient expertise. I finish with one very specific suggestion for a research project.

3.2. Problems of star cluster dynamics

Broadly speaking one finds that papers on the dynamics of star clusters come from two different kinds of authors: those who have made it their lifetime's work to study these systems, where the problems are set by a long-term agenda; and those who often work in other fields, but happen to be inspired by some current problem in the dynamics of star clusters, usually for reasons connected with new observations. An example of the latter is the work on modelling tidal tails, which I summarised briefly earlier in this volume. An example of the former is the work on rotating stellar systems summarised by R. Spurzem; though it is new and valuable research, it belongs to a line that can be traced back at least half a century.

Table 1. Topics in recent observational papers on globular clusters

Topic	Number of papers
Globular cluster systems	18
X-ray sources	9
Young globular clusters	8
Mass function	6
Primordial binaries	5
Neutron stars	5
Structural parameters	4
Tidal tails	3
Collision products	3
White dwarfs	3
Galactic orbit	3
GC and galaxy formation	2
GC near the Galactic Centre	1
Planets in GC	1
Stellar evolution in dense environments	1

In order that these two flavours of research don't stray too far apart, and to find some pointers for problems that might be important in the next few years, I have informally surveyed observational papers on globular clusters in a recent 12-month period (using ADS), to find those which either have an impact on dynamical problems, or could benefit from theoretical study. Table 1 lists the results, ordered by numbers of papers in each scientific category, for which I simply used my judgement on the abstract of each paper.

The numbers in the column do not matter a lot, as they depend on how finely one divides each topic. (If there had been a classification "degenerate stars", instead of neutron stars and white dwarfs, it would have come near the top of the list.) Nevertheless, the emphasis on cluster systems is unmistakable, and yet nothing was said about this at this symposium, and very little in the posters. The topic of young globular clusters was probably also under-represented. Numbers apart, the presence of *any* topic on the above list should stimulate theorists to take an interest.

3.3. A very specific research project

There now exist several methods, which I reviewed briefly earlier in this volume, by which one can quickly (but approximately) follow the dynamical evolution of a globular cluster, starting with some initial structure and mass function. After something like 12Gyr of evolution, one can then compare the result with one of the well observed globular clusters of the galaxy, using data on the surface brightness profile, kinematics, and the mass function, sometimes at several radii. (Actually the modelling of globular clusters, even with equilibrium models such as variants of King's models, is not an active industry at present. One wonders if there is not just too much data for a satisfactory solution!)

Now one would like to close the loop, i.e. adjust the initial parameters so as to improve the fit with the observational data at the present day. By iteration, there seems no reason in principle why one cannot thus arrive at a plausible example or range of initial conditions for the cluster in question. Any reasonable technique of optimisation should work. Such a tool would be of considerable value in modelling globular clusters, which is certainly needed for the interpretation of such data as the local mass function, and it would also be useful to suggest initial conditions to be used in more exact N-body simulations.