Extragalactic Star Clusters
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Conference Summary

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1. Introduction

This was a superb conference: scientifically exciting, and wonderfully enjoyable from every viewpoint. The biggest problem was, of course, that trying to absorb all the science has resembled drinking water from a firehose: there has been just too much of it to take in on the spot. So if the purpose of a conference summary talk is to dispense sage advice, then I will say that the best thing all of us can do now is simply to go home and think, and begin digesting this vast array of new material. IAU 207 is sure to be remembered as a launching point for many new directions and syntheses that will emerge from its stimulus over the next several years.

2. Profiles and Directions

But of course a single sweeping remark or two will hardly do justice to what has taken place this week. An interesting comparison of this meeting can be made with another conference which took place 15 years ago, the landmark Harlow Shapley Symposium (IAU 126) in Cambridge, Massachusetts. That meeting, in 1986, was the first one in history devoted specifically to Globular Cluster Systems, and virtually everyone working in the field (about 160 participants) was there.

IAU 207 provided a cross-section of the remarkable growth of the field since that time. It has been a big meeting: almost 200 participants, 5 days, 60 talks, 85 posters, countless corridor conversations; and we all know of still more colleagues who for one reason or another were not able to come. If anyone needed clear evidence that the study of star clusters in galaxies is in excellent health, these numbers by themselves tell the tale.

But there are even better diagnostics of health. An extremely important one is simply to look around and notice who is here. During the week we've been treated to all kinds of distribution functions, so let me show you one more: my best guess at the Age Distribution Function (Figure 1) for the people at the meeting. It seems to me that this ADF represents a very nearly optimum mix! It is nicely peaked just where it should be for a vibrant field with a bright future, while maintaining a strong tradition extending back many years.[1] Alternatives – such as curve (a) (where there would be little continuity or perspective), or

[1]This distribution is fundamentally *not* bimodal!

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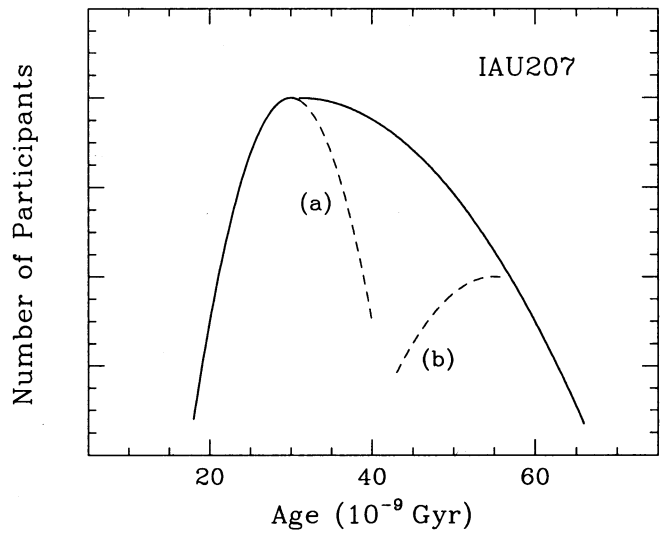

Figure 1. A rough ADF (age distribution function) for the people at the Symposium, plotted as the solid line. Curves (a) and (b) represent hypothetical possibilities that are less desirable.

the even worse case (b) (where either the field is dead or its funding has been removed) – are not as attractive.

Another sort of diagnostic is that of the mix between theory and observation. Do we have the right balance? This field is unquestionably an observation-driven one, and it is entirely appropriate that most of our time this week was spent presenting and debating new data. But there are many instances where we cannot go much farther into the underlying astrophysics without a lot of input from theory. A healthy leavening of theoretical interpretation and modelling was sprinkled throughout the week – and very noticeably more than at IAU 126 – but my impression is that we could profit from a bit more. Progress in modelling relevant to globular cluster systems falls into three major areas:

Stellar Structure and Evolution: Modelling the evolution of stars through all their complex nuclear burning stages, and beyond, is unquestionably one of the most mature and advanced areas in all of astrophysics, and several papers given at this meeting show that it continues to drive toward still higher levels of sophistication. The various evolutionary stages of low-mass stars are understood in considerable detail, and isochrones match up with real star clusters with a quality unheard of at the epoch of IAU 126. Certain problems, however, like the "second parameter" issue, have proven surprisingly resistant to easy solution and continue to plague us. It is becoming increasingly harder to avoid the view, expressed from time to time in the past, that the distribution of stars in the color-magnitude diagram, and their differences from one cluster to another, are a complex function of many *mutually coupled* variables including (but probably not restricted to) the detailed chemical abundances $\{Z_i\}$ including helium, CNO, the iron group and others; age; rotation; mass loss; binarity; magnetic field; and

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the many possible effects of the stars' environment, including the dynamical state of the cluster and the wide range of stellar interactions and collisions that become possible deep within the cluster cores. We can no longer expect that just one or even two of these variables (such as the traditional age/metallicity pair) are sufficient to explain the entire spectrum of real clusters to the level of detail that our new data demand.

Stellar Dynamics: The dynamical evolution and survival of star clusters in the tidal fields of their parent galaxies is another long-standing issue, and (since it relies only on the action of gravity) is a simple problem to formulate in principle. This subject has grown out of a number of classic papers based on analytic arguments, but it was not until the advent of full-scale contemporary simulations incorporating all the various dynamical erosion mechanisms that we have begun to glimpse the dynamical states of realistic clusters in their full complexity. The papers presented this week did a particularly effective job of demonstrating to us that the low-mass end ($< 10^5 M_\odot$) of the cluster mass spectrum experiences strong and rapid erosion over the first $1 - 2$ Gyr. This process seems convincingly capable of turning an initial power-law mass distribution $n(\mathcal{M})$ into the presently observed mass distribution for old globular clusters, with its well known Gaussian-like shape in $n(\log\, \mathcal{M})$ which shows up so persistently in *all* galaxies. We can hope that it will soon be possible to move into more advanced problems such as the relation of the mass spectrum to the age distribution of the clusters, the galactocentric distance, the type of parent galaxy, and other factors.

Cluster Formation Theory: The papers presented this week laid out some excellent discussions of key concepts, but there is clearly a long road ahead. Exactly how does a star-forming region such as a giant molecular cloud transform some small part of itself into a few gravitationally bound star clusters? What determines the mass fraction (generally less than 1%) that ends up in long-lived clusters? Even the most basic features of the problem such as the roles of gas pressure, density, turbulence, external shocks, total mass, and magnetic field are still being hotly debated. This is clearly a tough problem, relying as it does on messy, complex, and highly nonlinear gas dynamics (and magnetohydrodynamics) on several coupled scale lengths: protogalactic potential wells 100 kpc across, containing kiloparsec-sized GMCs, which in turn contain protocluster cores a few parsecs across and even smaller protostellar cores. In the early stages of galaxy evolution, interesting action can be expected to be happening on all these scales at once.

The theory side of this subject is thus in an extremely interesting stage of development: stellar structure and evolution, with many major successes to its credit, is pushing forward to a new level of still more advanced detail; the stellar-dynamics simulations of star clusters have just now broken through to answering some of the important first-order questions convincingly and hold considerable promise for further answers to long-standing questions; while the modelling of star cluster formation is starting on the road to quantitative explanations for the structures of star clusters at birth, and their mass distribution.

The diversity of the field today was nowhere more evident than in the many poster papers on display:

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- 6 papers on color-magnitude studies of Milky Way globular clusters,
- 7 papers on younger clusters in the Milky Way,
- 2 papers on field-star populations in the Milky Way,
- 5 papers on stellar structure and modelling of color-magnitude diagrams,
- 5 papers on the structures of star clusters at formation and their host giant molecular clouds,
- 12 papers on Magellanic Cloud star clusters and field populations,
- 8 papers on star clusters of all types in M31 and M33,
- 5 papers on clusters in Local Group dwarf galaxies, both irregular and elliptical,
- 6 papers on young star clusters in nearby spiral galaxies, 5 more papers on clusters and gas in interacting pairs of galaxies, and 5 more papers on clusters in starburst galaxies,
- 13 papers on globular clusters in elliptical galaxies, from NGC 5128 outward to the Coma Cluster,
- 4 papers on integrated spectral features of star clusters,
- 6 papers on theoretical concepts for star cluster formation.

The central spine of this subject is still the sequence of topics starting with the Milky Way globular clusters (CMDs, abundance studies, stellar evolution, halo kinematics, cluster dynamics) and continuing outward to old-halo clusters in other galaxies, particularly ellipticals where globular clusters are most populous. This core sequence has developed increasingly high standards and a long tradition. But we can now add to the mix a wonderful range of new findings about star clusters, without regard to age, mass, or metallicity, in many types of environments: the Magellanic Clouds and M33, starburst galaxies, colliding and interacting galaxies, dwarf irregulars, and even the giant molecular clouds and the gaseous environments from which clusters are made.

These papers, as well as the oral presentations, also showed the payoff of our development of new tools and techniques over the past decade. At the time of IAU 126, computer simulations were in their infancy, no one had a 8- or 10-meter telescope, and everyone was looking forward to what HST might show us when it was launched. Today, the promise of HST particularly with its superb imaging has been amply fulfilled, and the contributions of the new generation of 8-meter-class telescopes, mosaic large-field cameras, infrared cameras, population synthesis codes, and computer simulations of all kinds are all now on the front line.

3. How to Innovate in Three Easy Steps

Like scientists in every field, we live for and thrive on new discoveries. But what is the prescription for finding something genuinely new? Aside from our ability to think, there really are just three ways for us to do that:

(1) *Get lucky.* We've all had our share of luck, both good and bad, and many discoveries have come about by plain accident. But of course this route does not make much of a reliable general strategy. Fortunately, there are alternatives:

(2) *Do a survey.* If we don't know what to look for, then the obvious course of action is to look for *everything*: cast a wide net and see what turns up. Almost invariably we will encounter surprises and new avenues. The results of surveys, some of them on impressively large scales, were very much in evidence here all week: Milky Way open clusters, color-magnitude surveys of clusters in the Milky Way and Magellanic Clouds, GMC structures in the LMC, globular clusters in M31, dwarf galaxies, NGC 5128, spectra in giant E galaxies and the Fornax environment, and more. Exploring their full potential will take the next several years, but we are going to learn a considerable amount from all of these.

(3) *Diversify.* Make new connections with other research areas, *especially seemingly unrelated ones.* This is invariably a powerful way to inject new ideas into everyone's discussions. This week, the benefits of bringing together the "young" and "old" star cluster and stellar populations communities have been very evident.

Years ago, the people working on globular clusters and halo-star populations as traditionally defined, formed a very different research community from those working on star-forming regions, GMCs, and the youngest stellar populations, and little communication passed between them.[2] Yet each of them had much to tell the other. Links finally began to build throughout the 1990's. One of the signal accomplishments of this conference, in my view, has been to solidify these connections to the point where it no longer makes sense to view these areas as distinct. Thus, for example, we can now put an image of the Orion Nebula Trapezium Cluster side-by-side with a picture of Messier 15, and comfortably see them as members of the same extended family, albeit not exactly siblings.

What young objects will eventually evolve into globular clusters as we traditionally think of them? This question came up throughout the week in many different disguises. The main action of star (and cluster) formation happens within GMCs of all sizes. In order of increasing number $N_\star$, we can define a rough sequence starting with small coeval clumps of stars, through more populous associations and their more tightly bound cousins called open clusters, up to "young massive clusters", and finally globular clusters (see Figure 2). It is remarkable and sobering to realize that this last group, despite their high individual masses, make up much less than 1 percent of all star formation and that

[2]Strangely, recognition of the very real physical relations among old and young star clusters in these various places was held back even by terminology. The biggest young clusters found in starburst and gas-rich irregular galaxies (and that are logical progenitors to the classic old-globular clusters) have been referred to variously as "super star clusters", "populous blue clusters", or "young massive clusters", among other terms. Contrarily, we might just as well refer to the classic old-halo globular clusters as "ancient super star clusters".

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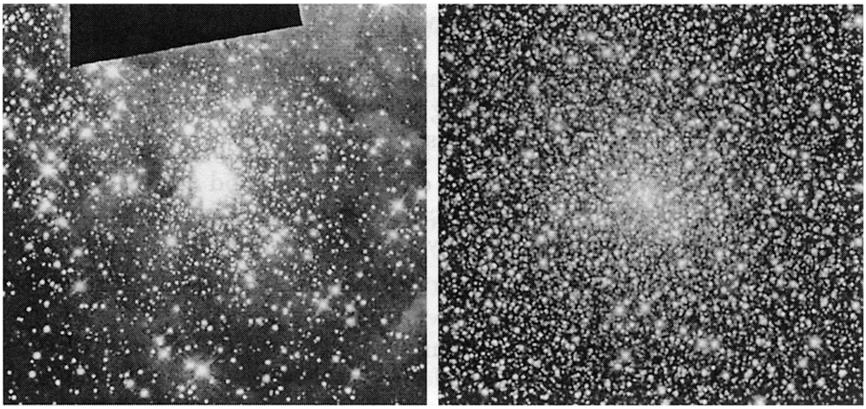

Figure 2. (a) The young star cluster R136 at the center of 30 Doradus (HST/WFPC2 image by John Trauger and James Westphal; NASA/AURA/STScI). (b) The Milky Way globular cluster NGC 7078 = M15 (Hubble Heritage Team image, NASA/AURA/STScI). The comparison between these two clusters is deceptive, because R136 (a "young massive cluster") is still many times less massive than M15.

almost every star probably forms within one of those smaller and more weakly bound modes. In Dean McLaughlin's phrase, globular clusters are "special but regular": regular in the sense that they are found ubiquitously in all kinds of galaxies, but special in the sense that some very extreme conditions seem needed to form them – gas at the highest densities and star formation at the highest efficiencies. The right arena for forming the compact, $\sim 10^5 - 10^6 M_\odot$ stellar systems we call globular clusters still seems to be deep within the very massive $\sim 10^8 - 10^9 M_\odot$ clouds that inhabited the pregalactic era in large numbers but which are much rarer in today's universe. Most of the things called super star clusters or young massive clusters still fall well short of what our globular clusters must have looked like at those young ages.

A more accurate comparison between very young and very old star clusters might be the one shown in Figure 3. NGC 3603, a cluster in the southern Milky Way, is just a few Myr old and several thousand $M_\odot$ big. It is striking to realize that its true analog at the opposite end of the age scale is probably something like Palomar 13, one of the smallest known old-halo globular clusters and one which is thought to be nearing the end of its long story of dynamical erosion from the tidal field of the Galaxy.

4. What Do We Need to Do?

Conferences are remembered for the questions they posed as well as for the new material that was on display. If it is fair to bring this meeting to a close by articulating the goal that has been constantly in front of us, I think it would be this: The story we want to reconstruct is the complete life history of a star cluster, from its emergence within a GMC to its role within the larger

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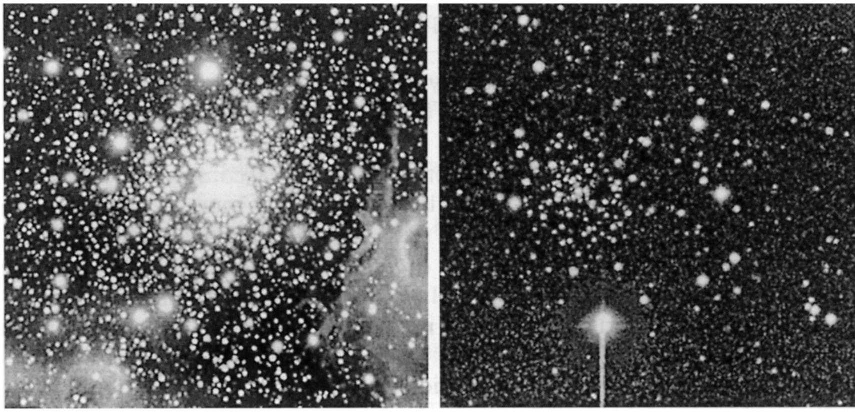

Figure 3. (a) The young star cluster NGC 3603 in the southern Milky Way (VLT/ANTU image PR-38a/99, ESO). (b) The old and sparse Milky Way globular cluster Palomar 13, well on its way to dissolving into the field (Las Campanas Observatory image by M. Siegel, S. Majewski, C. Gallart, K. Cudworth, and M. Takiyama). This comparison is more nearly correct, since both clusters were likely to have had very similar masses at birth (several thousand $M_{\odot}$).

environment of its parent galaxy. This storyline, as we all know, links to a wide range of more specific astrophysical questions:

– What was the sequence of events in the early history of large galaxies, both spiral and elliptical? What were the typical sizes of their progenitor gas clouds, how many major episodes of formation did they go through, and what was their chemical evolution history?

– What can clusters tell us about the kinematical state and dynamical history of such galaxies?

– Why are the formation histories of field halo stars in many, perhaps most, galaxies different from those of the globular clusters?

– Are the oldest globular clusters in giant E galaxies really the same in age and abundance as the ones in the Milky Way and M31? Why did they form at such high relative efficiency?

– What fraction of a globular cluster system within a large galaxy arose from the different mechanisms of hierarchical formation, later major mergers, and continuous accretions?

– What conditions are needed within a GMC to form a gravitationally bound, massive star cluster, and what governs the mass distribution function of the star-forming clumps and clusters within a GMC? What determines the star-forming efficiency within any one of these regions, and thus whether it can survive for the long term?

– Within classical globular clusters, what parameters govern the details of the distribution of stars in the color-magnitude diagram? Are the most important parameters different ones for different clusters, and how are these governed by environment?

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– How will more advanced stellar physics influence our estimates of cluster ages and compositions?

– Can we trace out the detailed dynamical histories of individual old globular clusters, including their orbits in the halo from proper motions and tidal tails?

The list is long and we are still some way from a complete picture. But a real sense of optimism has emerged that we have many more of the pieces of the puzzle now in front of us. What do we need in order to go further?

First, I suggest that we need to diversify a bit more. The star cluster timeline we want to reconstruct must be pushed back to *negative* ages; that is, protocluster gas clouds which have not yet begun their first star formation. Closer association with the GMC and interstellar medium communities – mm and sub-mm studies of star-forming regions both at high resolution and in survey mode – should tell us much. The beginnings of such links were evident here, but must be deepened. On the modelling side, as suggested above, we need more (and more quantitative) theoretical concepts for cluster formation, which will quickly become closely connected with the larger issue of star formation, itself a major unsolved problem area of astrophysics. Both areas will benefit.

Also on the observational side, the new large telescopes – as well as HST, and farther downstream, NGST – will continue to pay rich dividends in many directions: large samples of cluster velocities and halo kinematical modelling; high spectral resolution and studies of cluster abundances and ages; and the exploitation of the infrared for the characteristics of the heavily reddened objects in the Galactic bulge and in other galaxies, as well as direct photometry of the bright stars in star clusters within other galaxies.

Above all, as in every branch of astronomy we need to have large doses of both enthusiasm and patience. Even with the best combinations of observation and theory that we can assemble at any given time, unambiguous results are rare, and we spend much of our time exploring uncertainties and error bars rather than achieving answers. But we can go onward with total confidence that there is much new to find, and with so much new material on the horizon, can our next gathering be long in coming? With these thoughts in mind, it is time to bid everyone a warm *hasta la lluego* , and a safe journey home.

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