Mem. S.A.It. Vol. 87, 666

Memorie della

Conference summary: the Bologna–M16 Questions

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Abstract. Rather than attempt to summarise an entire week of excellent talks, I will instead take the material covered in this meeting as a starting point and from it produce a list of questions which cover a number of outstanding questions within the field of stellar cluster formation and evolution. I have five questions in total. Given the location (Bologna) and nature (Modest-16) of the meeting, I label my questions the *Bologna-M16 Questions*.

Key words. Stellar clusters – Stars: neutron stars – Stars: black holes – Galaxy: globular clusters

1. Introduction

Star clusters are indeed good laboratories in which to study astrophysics, dynamics, and fundamental physics. This broad reach is reflected in the conference programme, with talks concerning the overall dynamical evolution of stellar clusters, and their myriad of exotic contents. I will not give a summary of the many (excellent) presentations here. For one thing, summaries are available in this proceedings. Rather I will put together a list of (five) questions which cover some of the interesting future work which is needed in the field. As the conference was hosted in Bologna, and designated MODEST–16, I dub these five questions *The Bologna–M16 Questions*

This conference summary is written in a deliberately informal manner in keeping with the talk as delivered. I summarise each question with a three-word phrase followed with further description. I have avoiding citing talks given at the meeting but I do draw attention to the published work of participants and others.

2. Q1: Win or lose?

In this first question, we consider stellar clusters as factories producing *exotica*. It has long been understood that globular clusters are good at producing interesting and unusual objects through a combination of dynamical and hydrodynamical interactions. This is certainly true in some cases, for example low-mass X-ray binaries (LMXBs) and millisecond pulsars (MSPs) are both found in relatively large numbers in globular clusters. This can be understood as LMXBs can be produced by encounters between single neutron stars and binaries (e.g. Davies & Benz 1995) which often result in the (more-massive) neutron star exchanging in to the binary. It is possible that tidal capture can also occur when a single neutron star encounters a single main-sequence star or red giant (Fabian, Pringle & Rees 1975). MSPs are also produced in relatively-high numbers as they are the products of LMXBs.

However the picture is not so clear for all flavours of exotic objects. For example, the production rate of cataclysmic variables (CVs: binaries containing a white dwarf receiving mass from a low-mass donor star) may in fact be *lower* in globular clusters than in the field. The reason is that CVs are produced in the field of the Galaxy relatively frequently as the product of binary evolution with binaries containing an intermediate-mass star with a lower-mass companion. It turns out that in the most-crowded globular clusters these binaries are vulnerable to being broken up via encounters with a third star (Davies 1997). CVs may however be produced in globular clusters through dynamical interactions, probably most importantly those involving a binary and a single star. Thus there is competition between encounters which destroy the binaries which would have made CVs on their own and those encounters which produce CVs from other binaries.

A similar competition occurs when one considers blue stragglers. Blue stragglers are observed in all globular clusters. They occupy a region of the main-sequence above the turn-off of the cluster. In other words, they would appear to be main-sequence stars which are more-massive than the current turn-off mass of a given cluster. It has long been understood that blue stragglers can be formed by either a recent collision between two main-sequence stars, or by mass transfer within a binary. Indeed an interplay between these two processes may lead to a blue straggler population which is relatively similar throughout all globular clusters (Davies, Piotto & de Angeli 2004).

Regarding the production of exotic objects in globular clusters, one should note that the post-encounter evolution of objects produced via dynamical or hydrodynamical encounters can be highly uncertain. Questions remain for example as to whether tidal capture can produce a binary or alternatively lead to the terminal swelling of the envelope of the captured star which then smothers its companion within a common envelope of gas. One should also recall that neutron stars and black holes may receive natal kicks when they form. Such kicks may greatly exceed the escape speed of stellar clusters. It could well be that all neutron stars observed within binaries in globular clusters today were made in a subset of core-collapse supernovae known as electron capture supernovae (Ivanova et al. 2008).

3. Q2: More than two?

Our second question can be usefully rephrased to: *what is the effective number of stars involved in encounters?* Single-single encounters clearly involve two stars, binary-single encounters three stars, and binary-binary encounters four. However things are not as simple as they might at first seem. The key point to realise is that other stars may come into the *fray* during the encounter. For example a transient triple is produced in many binary-single encounters. A fourth star can encounter this triple before it is broken up into a binary and a single star. Whether such encounters with additional stars are common depends on the ratio of two time scales: the time it takes for the temporary triple to resolve into a binary and single star ($t_{\rm trp}$) and the time scale to have an encounter with a single star ($t_{\rm enc}$). It turns out that $t_{\rm trp}/t_{\rm enc}$ is a function of the number of stars in the cluster (N). For globular clusters (today) where N is typically $10^5 - 10^6$, $t_{\rm trp}/t_{\rm enc}$ is small, i.e. additional stars interfere with an on-going encounter only rarely. However, for smaller clusters, or in the initial dense lumps of globular clusters (where $N \sim 10^2$) such interference will be common (Geller & Leigh 2015).

The key point is that in order to properly model the effects of encounters in small N clusters or in the initial dense lumps of more-massive clusters, then one has to model each encounter embedded within the cluster allowing correctly for the influx of additional stars before an encounter is resolved. Though not unsurmountable, this requires additional work to perform a simulation of such clusters including properly the effects of encounters.

4. Q3: Chicken or egg?

Our third question concerns the formation and growth of black holes in stellar clusters. It remains uncertain whether any globular clusters contain intermediate-mass black holes. But here, we will consider supermassive black holes (SMBHs). The meaning of the question three is to consider SMBHs at the centre of nuclear stellar clusters in galactic nuclei and to ask: *Which came first, the black hole or the nuclear stellar cluster?*. It is worth recalling for example that the nucleus of the bulge-free spiral galaxy M33 contains a nuclear stellar cluster but no supermassive black hole. It is unlikely that any SMBH has been ejected (for example by a merger with another black hole) as such events come about from major mergers which would also have produced a stellar bulge which M33 does not possess. One could only reasonably conclude that no SMBH has formed in the nucleus of M33, yet it has produced a nuclear stellar cluster. Logic would then suggest that at least in some cases SMBHs form within nuclear stellar clusters, i.e. *after* the formation of nuclear stellar cluster. Indeed nuclear stellar clusters show a clear dichotomy between those containing an SMBH and those which do not (see fig. 2 of Neumayer & Walcher 2012).

If we assume that any massive black holes found in stellar clusters grew from stellar-mass black holes formed in core-collapse supernovae, then we need to recall that the majority of massive stars which undergo such supernovae are found in binaries. Further, mass transfer within a large fraction of these binaries will affect the supernovae taking place within them (Sana et al. 2012). Thus questions concerning black-hole formation and growth within clusters require an understanding of the details of binary evolution, which is an ongoing field of research in itself. Note for example, the recent work concerning the formation of black hole-black hole binaries of the type recently observed through their gravitational wave emission (de Mink & Mandel 2016; Marchant et al. 2016). If the majority of black holes receive significant natal kicks, then very few will be retained in stellar clusters. Further, should black holes be retained, and form a black hole-black hole binary which then merges because of angular momentum loss due to gravitational wave emission, the system may then be ejected from the cluster by the merger kick received by the merged black hole due to the asymmetric emission of gravitational radiation.

So, in order to make progress concerning black-hole formation and growth within stellar clusters, one must also make progress on the issues discussed above. In general terms, considering the observational effects black holes would have on stellar clusters is also a good way forward in our hunt for black holes within stellar clusters, for example the presence of an intermediate-mass black hole could effect mass segregation (Gill et al. 2008).

5. Q4: More than one?

Multiple populations are seen in the majority of globular clusters with different groups of stars possessing distinct chemical abundance properties. Their discovery represents one of the greatest challenges in modern astronomy as it had previously been thought that globular clusters would contain a single population of stars having formed together from one gas cloud, the remainder of which had been ejected by strong winds or supernovae within the first ten million years. Instead, we observe at least two populations in most clusters and in some cases several populations (e.g. Piotto et al. 2015). A sequence of star formation events has been suggested in order to explain the multiple populations observed in the globular cluster NGC 2808 (D'Antona et al. 2016). In general terms, it is hard to understand how first and second generations can be of similar sizes given that the second are likely derived from polluted gas released by a small subset of the first population (D'Ercole et al. 2008).

It could that a number of globular clusters began life as the nuclei of dwarf galaxies which were subsequently stripped. But, given that dwarf galaxies are also seen to possess globular clusters, not all globular clusters can have started out as the nuclei of dwarf galaxies. One approach to understanding the multiple populations seen in globulars is to understand better the situation when multiple populations are not seen, for example in rich open clusters. What are the differences in the early lives of globulars and open clusters? And what is the relationship between globulars and nuclear stellar clusters? What are the underlying stellar populations in the latter objects?

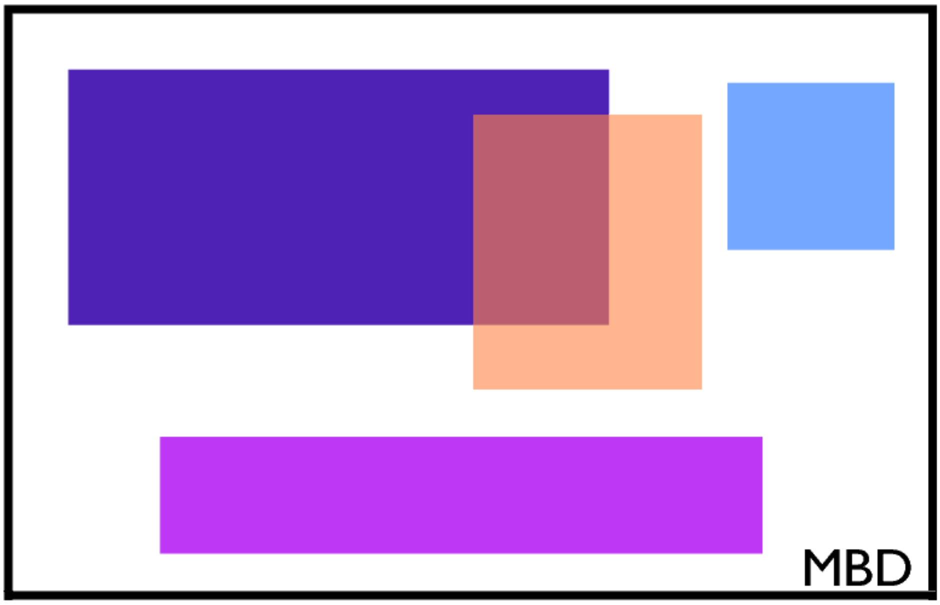

Fig. 1. An impression of a globular cluster (during the first 10-100 Myr) where star formation occurs in separate regions which then merge to form a single cluster. In some cases, stars in one region pollute the gas which then forms other stars. In recognition of the meeting location, I dub this the *Bologna Process*.

6. Q5: Stars and gas?

The M16 in the title refers to the designation of the meeting as MODEST–16. However, it is also amusing to recall that M16 – Messier 16 – is more often known as the Eagle Nebula. Made famous perhaps by observations taken by HST. Thus, in my final question here, I turn to the first ten million years of a cluster's existence, when stars were forming within a gas cloud, just as we observe in M16 today. A symbolic sketch of what might be going on is shown in Figure 1. The key idea presented here is that stars form in their own small groups from a small, individual region of the entire gas cloud. These groups will later mix and virialise so that we will see a single cluster today. Somehow, in a manner which in my view remains to be determined, some populations are able to pollute gas which subsequently forms other stars (shown in the figure as the overlapping regions). These polluting stellar populations may be distinct in terms of IMF, for example in being top heavy. Computationally modelling the first ten million years, resolving both the N-body dynamics and hydrodynamics remains a challenging problem, though progress has been made in recent years, particularly concerning the ejection of gas driven out by massive stars (e.g. Dale 2015).

Acknowledgements. I wish to thank Francesco Ferraro, his team, and the conference speakers, for an excellent meeting.

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