Report on the ESO Workshop on

12 Questions on Star and Massive Star Cluster Formation

held at ESO Headquarters, Garching, Germany, 3–6 July 2007

Markus Kissler-Patig[1]
Tom Wilson[1]
Nate Bastian[2]
Francesca D'Antona[3]
Richard de Grijs[4]
Dirk Froebrich[5]
Emmanuel Galliano[6]
Preben Grosbøl[1]
Kelsey Johnson[7]
Eric Keto[8]
Ralf Klessen[9]
Tom Megeath[10]
Marina Rejkuba[1]
Jürgen Steinacker[11]
Hans Zinnecker[12]

[1] ESO
[2] University College London, United Kingdom
[3] Osservatorio di Roma, Italy
[4] University of Sheffield, United Kingdom
[5] University of Kent, United Kingdom
[6] Universidad de Chile, Santiago de Chile, Chile
[7] University of Virginia, Charlottesville, Virginia, USA
[8] Harvard-Smithsonian Center for Astrophysics, Cambridge, Massachusetts, USA
[9] Universität Heidelberg, Germany
[10] University of Toledo, Ohio, USA
[11] Max-Planck-Institut für Astronomie, Heidelberg, Germany
[12] Astrophysikalisches Institut Potsdam, Germany

The Workshop "12 Questions on Star and Massive Star Cluster Formation" was held in Garching from 3 to 6 July 2007. The programme was set up to allow long (and fruitful) discussions around several questions connecting the formation of stars and star clusters. Here we summarise some of the discussions, and encourage interested readers to download the contributions from *http://www.eso.org/star07*.

In view of the booming fields of star formation and star-cluster formation, we had thought, back in mid-2006, to organise a meeting that would bring these two communities together. To an outsider, star formation and star-cluster formation might look like one and the same thing, yet these two communities rarely interact for various reasons. The main one is probably the distance of the studied objects. Star formation can be studied in great detail close-by, i.e. in our Milky Way where distances are expressed in parsecs, and the studied regions enclose typically a few hundred stars. In contrast, suitable targets for studying the formation of massive star clusters are only available in neighbouring galaxies and distances to them are rarely smaller than a few million parsecs – the studied objects enclose up to hundreds of millions of stars. The scales in which the two communities typically think are thus different and the time had come to try to connect them. Further, ALMA – the large sub-mm array – is now within reach and will boost both fields, exactly allowing to connect the two scales thanks to an increased sensitivity and angular resolution.

The format we have chosen for the workshop was a new one: we built the programme of the workshop around a number of questions to be addressed in dedicated sessions. We summarise here some (not all) of the discussed points. All presentations are available for download from the workshop web site *www.eso.org/star07.*

"How are the stellar and cluster initial mass functions related and how are they influenced by the star-formation history?"

The first question of the workshop was posed and introduced by Marina Rejkuba. It is an indisputable fact that star formation is hierarchical. The empirical evidence indicates that the initial mass function (IMF) of young embedded stellar clusters is a universal power law with a slope of 2.0, and that the stellar IMF follows a universal segmented power law in many different environments. The validity of the power-law form for the IMF was questioned in the discussion, but opinions remain divided. The theoretical arguments for the universal stellar IMF were presented by Ralf Klessen, while Hugues Sana and Jorge Melnick showed the pitfalls and problems in empirical determination of the stellar IMF in clusters and in the field. Andrés Jordán discussed the form of the initial old cluster-mass function.

The fact that the clusters undergo massloss and disruption on short timescales, leads to the composite nature of the field-mass function. Whether this composite IMF is steeper, or has the same slope as

Figure 1: The conference delegates collected in the entrance hall of the ESO Headquarters in Garching.

the star cluster IMF, has been shown to depend on the answer whether 20 clusters with 10^4 $M_\odot$ can produce the same IMF, with the same maximum stellar mass, as one cluster with 2×10^5 $M_\odot$. With respect to this point the two major theoretical works of Elmegreen and of Weidner and Kroupa disagree. Unfortunately, due to the often poorly known star-formation history of the observed field, and the problems to establish the frequency of binaries in the population, the observational evidence seems to be still inconclusive. Until the errors of the IMF derivation can be reduced, the question remains open.

"What are the effects of stellar feedback?"

In this session negative feedback effects, namely the destruction of clusters, were addressed. During the collapse and fragmentation of a molecular cloud into a star cluster, only a modest amount of the gas is turned into stars. The stellar winds, photoionisation, and supernovae from massive stars inject enough energy into the gas to remove it extremely rapidly (in less than a dynamical crossing time). This rapid gas removal can leave a cluster significantly out of equilibrium. If the star-formation efficiency is low enough (~ 30 % of the initial fraction of gas turned into stars) the entire cluster can become unbound.

Nate Bastian reviewed the physics and some recent observations of this process. In particular he discussed recent N-body simulations of the effects of gas removal on the early evolution of clusters. He also reviewed recent attempts to quantify the amount of infant cluster mortality, with most studies finding values of 60–90 % of young clusters being disrupted in the first 40 Myr of their lives. Sabine Mengel focused on the young massive cluster Westerlund 1 in the Galaxy. She concluded that the star-formation efficiency of this cluster was quite high (> 60 %). Dieter Nürnberger concentrated on another young massive cluster in the Galaxy, namely NGC 3603. On the basis of multi-wavelength observations he pointed out that this cluster is part of a much larger area of star formation. He also showed examples of how the high-mass cluster stars affect the ISM and the young sources in their neighbourhood.

"What is the demographics of star formation in our Galaxy and others?"

In studies of galactic star formation, young stars have traditionally been separated into two demographic groups: isolated stars and clustered stars. This picture is evolving for many reasons. Tom Megeath posed this question. He showed Spitzer surveys of the giant molecular clouds in the nearest 1 kpc revealing the presence of large clusters, small groups, and large numbers of relatively isolated stars. These surveys suggest that isolated stars and dense clusters are extremes of a continuum. Galactic studies provide the opportunity to study physical processes in great detail and trace the distribution of low-mass stars which dominate the mass but are undetected in extragalactic observations. Detected extragalactic clusters are much more massive than clusters near the Sun such as the Orion Nebula Cluster. Frédérique Motte suggested that our Galaxy contains large clusters which overlap with the continuum of observed extragalactic ones. Arjan Bik presented a programme to obtain infrared spectroscopic maps of young embedded clusters in our Galaxy; infrared spectroscopy of the massive stars are needed to determine the membership, age and size of these highly reddened Galactic regions.

Finally, there was a discussion of how best to characterise the clusters, associations and complexes of star formation in our Galaxy and others. Nate Bastian introduced the minimum spanning tree analysis (see Figure 2) and applied this to Spitzer surveys of nearby molecular clouds and the distribution of OB stars in other galaxies. This analysis suggested hierarchical structure with no preferred scale. Mark Gieles showed a minimum spanning tree analysis of the Small Magellanic Cloud where they segregated sources by age. The youngest stars showed clear hierarchical structure while the distribution of the oldest stars was indistinguishable from a random structure, indicating that structure is erased as the stars migrate from their birth sites. In summary, the discussion of this question motivated the need to find Galactic analogues of extragalactic clusters and associations. Furthermore, it demonstrated the need for new methodologies for analysing structure on many different spatial scales, such as the minimum spanning tree or wavelet-based multi-resolution techniques.

"How did star formation proceed in Globular Clusters?"

In recent years, research on these very old systems has shown that they are not the 'simple stellar populations' we thought they were; this topic was introduced by Francesca D'Antona. There is precise spectroscopic evidence that chemical anomalies are present, generally involving about 50 % of the stars in each globular cluster (GC). Anomalies are found in practically all clusters observed so far. Anomalies are also present among unevolved stars, so that they cannot be imputed to 'in situ' mixing in giants. In particular, sodium is enhanced and oxygen depleted with respect to the normal values in the field population II. This, in the end, means that about half of the stars in the clusters (a second generation) are born from matter contaminated by

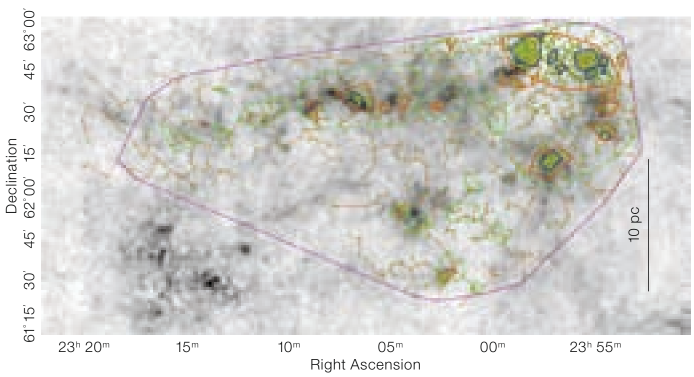

Figure 2: Example of a minimum spanning tree, presented by Nate Bastian and collaborators, revealing the hierarchical structure of star formation (Figure courtesy Gutermuth et al., in preparation).

products of hot CNO burning in stars of the first generation, but not by supernova ejecta, as the metallicity stays constant. The culprits may be the ejecta of massive Asympotic Giant Branch (AGB) stars, as pointed out by Paolo Ventura, or even the envelopes of massive rotating stars, as presented by Thibaut Decressin. The two suggestions imply very different time scales for the formation of the second stellar generation (a few million years, or many tens of millions of years after the formation of the first-generation stars). The number ratio of the two generations, however, implies that the first generation in the pristine globular cluster must have been much more massive (by a factor of 5–10) than today's globular clusters, and this may provide us with hints about how to model the second stage of star formation. Additional evidence of nuclear processed matter is the presence of stars with helium content higher (and even much higher, implying an incredibly high slope of the He enrichment function dY/dZ) than the standard Big Bang abundances. Beautiful observations of splitting of the main sequences in two clusters were presented by Antonino Milone, on behalf of Giampaolo Piotto's group. This view was enlarged to consider low-mass dwarf galaxies by Michael Hilker.

"What governs protostellar mass accretion?"

The physical processes at work in the main mass accretion phase during the process of star formation were presented initially by Dirk Froebrich. In particular, the question of what are the main physical forces and/or initial conditions responsible for converting the observed core mass distribution into the stellar IMF was discussed. It became apparent during the discussion that, beside gravity, the initial specific angular momentum of the core most likely is the main influence on the time dependence of the mass-accretion rate onto the central object. In turn this is, together with the structure of the object, what determines the time evolution of the protostellar observables (e.g. T_{bol}, L_{bol}). Magnetic fields are considered to also be important in determining the accretion rates, which reach much higher values than predicted by self-similar collapse solutions. Further impact on the time evolution of the objects might come from competitive accretion. However, no agreement could be reached on how to interpret the observational evidence.

"How does spiral structure affect star formation?"

Preben Grosbøl drew the attention back to extragalactic objects. Many grand-design spiral galaxies display a concentration of H II regions and OB associations in their arm regions. The increased number of very young sources in the arms suggests an enhanced star-formation rate which could partly originate from a higher surface density in the arms due an underlying density wave. On near-infrared *K*-band images of late-type spiral galaxies, one frequently observes bright knots aligned along the arms. The colours of these knots indicate that they are very young, massive stellar clusters. The number and brightness of such sources correlate with absolute magnitude and spiral perturbation of the host galaxy. The alignment is seen mainly in the galaxies with strong spiral arms, suggesting a triggering mechanism associated with the underlying density wave. This could support a scenario in which young, massive clusters are disrupted in an early phase, since fainter, aging clusters are not observed downstream, as expected due to the relative motion between material and wave.

"How important is 'primordial' mass segregation in the context of massive star cluster formation and evolution?"

This question was posed by Richard de Grijs and led to a controversial discussion. Observations of young clusters in the local Universe show that almost every single cluster is significantly mass segregated, out to radii well outside their cores. This is particularly puzzling for the youngest star clusters, given that their ages are often only a fraction of the timescales required for dynamical effects to become significant on cluster-wide scales. If there is significant, possibly 'primordial', mass segregation within a cluster at the youngest ages, and hence a possible spatial dependence of the IMF (i.e., in the sense of preferential formation of the more massive stars in higher-density environments), this will have important consequences for the accuracy of the physical output parameters.

Joana Ascenso challenged this view. From a series of Monte Carlo realisations of non-segregated synthetic clusters with a standard IMF and a surface density distribution, she performed the 'standard' mass-segregation analysis. Surprisingly, she found a similar degree of 'primordial' mass segregation as claimed in the observational studies of de Grijs and Gouliermis for young clusters in the Large Magellanic Cloud, by Espinoza in the Galactic Centre Arches cluster, and by Brandner in Westerlund 1. Enrico Vesperini used extensive N-body simulations to show that early mass segregation in young clusters may have a dynamical origin. Despite the animated discussion following these thought-provoking presentations, the jury is still out on the basic underlying question of the importance or even the reality of primordial mass segregation.

"What is the relationship between the properties of star clusters and the environments from which they form?"

The environment of massive star-cluster formation is determined by a large number of parameters, including pressure, density, temperature, turbulence, magnetic fields, metallicity, gas content, galactic rotation (or lack thereof), and triggering mechanisms. Of course, many of these parameters are not orthogonal. The challenge, posed by Kelsey Johnson by this question, was to ascertain which of these parameters can essentially be neglected and which may have a significant impact on the properties of the resulting cluster(s). For example, one might expect metallicity to play a role in the properties of the resulting cluster, yet the few observed ultralow metallicity systems (e.g. IZw18, SBS0335-052) show very diverse modes of cluster formation, suggesting that metallicity (at least down to this abundance) does not play a dominant role. Detailed studies of the relation between specific frequency of globular clusters and galaxy type may provide important insight. However, this is a blunt tool, and raises the challenge of relating the role of macroscopic phenomena to local physics. A recurrent theme in the presentations of this session has been the importance of star-formation efficiency to cluster formation. However, this then begs the question of what primarily determines the star-formation efficiency. On the macroscopic scale, perhaps the most plausible answer is pressure, but it is not yet clear what subtleties, which may have a secondary role, are hiding in the microphysics; we must keep in mind that star formation is a local process. Although it is currently the fashion to accumulate large data sets with impressive statistics, in-depth case studies are still critical if we wish to disentangle all of the ingredients affecting massive star and star-cluster formation.

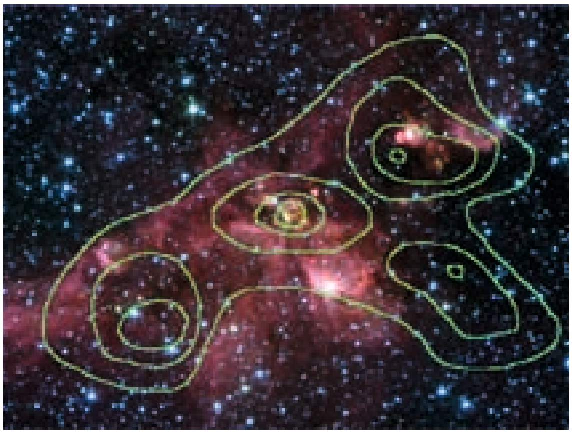

Figure 3: A massive star-forming region, presented by Eric Keto, illustrating massive accretion flows. The figure shows an overlay of contours of emission from molecular gas on a background image of mid-IR emission from Spitzer Space Telescope data. The central cloud encloses a particularly massive flow of 10^3 $M_{\odot}$/yr into the centre of the star cluster seen in the IR. The innermost contour is about 30″ in diameter (0.9 pc at 6 kpc).

"Which physics determine the stellar upper mass limit?"

Finally, Hans Zinnecker, Eric Keto, Carsten Weidner and Hugues Sana set out to answer this question. The most massive stars in the Galaxy are typically found in a group of several similar stars at the centre of an OB cluster, for example, the Orion Trapezium. When we look at a very young, embedded OB associations still in formation, such as G10.6-0.4, we see a massive molecular accretion flow into the centre of the cluster. Thus we expect the most massive stars in the Galaxy to form at the centres of such cluster-scale accretion flows (see Figure 3). The accretion velocities indicate that the flow is a 'cooperative accretion flow' drawn by the cooperative gravitational pull of the combined mass of several O stars at the cluster centre. Within a few thousand AU of the O stars, the molecular accretion flow becomes ionised, but continues in toward the cluster centre because the escape velocity from the co-op of the stars exceeds the ionised sound speed. The ionised accretion flow spins up into an ionised accretion disc at the cluster centre. Because the dust that was originally in the molecular accretion flow is destroyed by the high temperatures and densities in the disc, accretion can continue onto the individual stars in the co-op, unimpeded by the intense radiation pressure on dust. Secondly, in the fully ionised flow there is no outward pressure between the hot ionised and cold molecular gas to impede the flow. Thus the cluster-scale cooperative accretion flow sets up these two conditions that allow accretion onto very massive O stars despite the presence of outward forces of radiation and thermal pressure. The observational evidence, and more of the physics of the upper stellar mass limit, are reviewed in the recent Annual Reviews of Astronomy and Astrophysics article by Zinnecker and Yorke.

Overall, the workshop certainly left us with more questions than answers, but the format was a success as the workshop was dominated by long and fruitful discussions. The two communities working on star formation and star-cluster formation moved a step closer towards each other and there is good hope that they will merge in the epoch of ALMA.

Acknowledgements

We wish to acknowledge Christina Stoffer, who managed all the logistics of the workshop, as well as Arjan Bik for his help in the local organising committee.

Announcement of a Workshop on

Science from UKIDSS

17–19 December 2007, ESO Headquarters, Garching, Germany

The workshop will take place a few weeks after the UKIRT Infrared Deep Sky Survey (UKIDSS) large Third Data Release (DR3). The purpose of the workshop is to provide a forum, bringing together European astronomers working on (or planning to work on) UKIDSS data, to hear about science being undertaken with UKIDSS, and to share knowledge gained in working with the data and ideas for exploiting the archive efficiently, in an informal atmosphere. The emphasis will be on work in progress. The workshop will include science and technical talks, and tutorials, as well as a summary of the current status of the surveys, and an opportunity to discuss the future direction.

Registration will be open from 15 September 2007 at *http://www.ukidss.org/esoworkshop.*