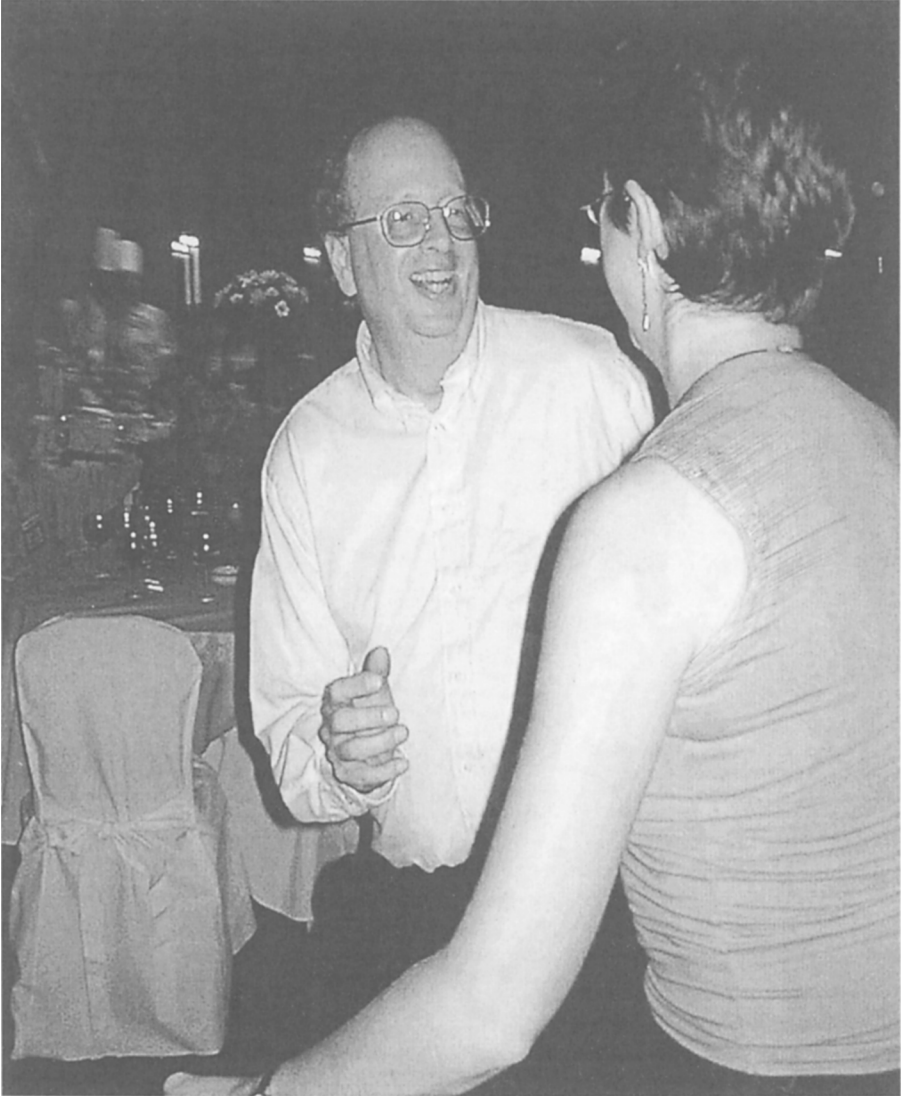# Part 5. Future Prospects and Conference Summary

Section A. Invited Reviews

Jay Gallagher enjoys a moment of inspiration from Carme Gallart while preparing his talk for the next day.

Extragalactic Star Clusters: Speculations on the Future

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Abstract. We discuss the future possibilities for extragalactic star cluster research with the expected new ground-based and space-based telescopes and instrumentation. Significant gains are expected due to improved angular resolution, sensitivity, and area coverage particularly in the infrared and radio, accompanied by progress in evolutionary and dynamical modelling. Improvements in angular resolution are anticipated, especially through new adaptive optics systems (e.g., Keck, Gemini, VLT), and interferometry (e.g., Keck, VLT, LBT, ALMA, SMA, SkA), and space instrumentation (e.g., Chandra, NGST), enabling studies even of deeply embedded, forming extragalactic star clusters. Tidal disruption of Galactic clusters becomes observable through wide-area surveys such as the SDSS, VISTA, PRIME, including proper motion measurements through high-resolution imaging (e.g., HST, LBT, SIM, GAIA). Sensitive new optical and infrared spectrographs (e.g., HET, SALT, GranTeCan, Magellan, Keck, VLT, CELT, OWL, NGST) will push kinematic and abundance studies to new limits, allowing us detailed comparisons with model predictions. One important wavelength range for the study of young, massive star clusters, the far UV, appears to be neglected by future planned instrumentation.

1. Introduction

While research on extragalactic star clusters has accelerated during the past decade, this field has yet to achieve full maturity. In part this is due to the demanding angular resolution and sensitivity requirements for measurements of star clusters in galaxies. The complex nature of star clusters also plays a role. Figure 1 presents a simple analogy to the life of a star cluster. It arises from and is shaped at birth by a variety of factors, including the structure of the ISM and properties of its host galaxy. Once separated from its natal gas, stellar and dynamical evolution will largely determine the degree to which a cluster survives as a gravitationally bound system. After several Gyr the rate of change may slow, with an important exception in cases of cluster core collapse, and the system should evolve passively to resemble the ancient globular star clusters.

The evolution of a star cluster, while considerably more complicated than that of a single star, is yet much simpler than what occurs in galaxies. Despite their complications, star clusters are the brightest and best samples of coeval star formation. They preserve information about past star formation processes through their chemical abundances, initial mass functions, and overall structures and are the mainspring of the stellar evolution clock. Star clusters form in a range of environments extending from extreme starbursts to the lazy birth of stars in dwarf galaxies, e.g., Grebel (2000). This paper briefly reviews some aspects of the life cycles of star clusters before turning to speculations about the future of this research area. We focus on the early development of dense, massive clusters in our by no means complete selection of examples. Features of globular clusters are covered by Lee (2002), Fall (2002), and many other excellent reviews in these proceedings.

2.   Evolutionary Phases

The evolution of massive star clusters has been discussed throughout this conference. Table 1 summarizes a simple model for the early evolution of a massive star cluster, based on the scheme outlined by Kobulnicky & Johnson (private communication). Our main goal here is to place the evolutionary path in an observational context, so that we can consider how advances in technology might influence our ability to chart the evolution of star clusters. For this illustration we assume that the evolution of a region surrounding a super star cluster depends on the state of the cluster; e.g., the giant HII region appears after the ionization front from the cluster advances into the surrounding medium. A key point is that during the first 100 Myr of the life of the cluster, it will produce interesting observational signatures across much of the electromagnetic spectrum, from radio emission during formation and as a dense, compact HII region, to X-rays associated with stellar winds and supernovae.

Table 1.   Phases of Cluster Evolution

Stage	Signature	Span	Properties	Observations
I	Pre-formation	$-1 - 0$ Myr?	dense molecular gas	radio: mm-cm
II	Stellar birth	$0 - 1$ Myr	ultradense HII/dust	radio + FIR
III	Giant HII	$1 - 7$ Myr	HII/UV stars	UVOIR
IV	Supernovae	$3 - 30$ Myr	OB stars/SNe II	UVOIR, X-ray
V	Supergiants	~ 10 Myr	peak optical/UV L	UVOIR
VI	AGB	$0.3 - 2$ Gyr	extended-AGB+MS	OIR + FIR
VII	RGB	$>2 - 3$ Gyr	RGB dominates	OIR

An equally important factor is our ability to resolve structure within star clusters, and to distinguish them from their often complex host galaxy backgrounds. As illustrated in Table 2, this ranges from nearly full access to individual stars on the lower main sequence around the Milky Way to an ability to distinguish the most luminous young super star clusters at D$\sim$500 Mpc for an assumed angular resolution of 0.1″. For our current best cosmological model, $H_0 = 65$ km s^{-1} Mpc^{-1}, $\Omega_{matter} = 0.3$ and $\Lambda = 0.7$, we require an angular resolution of about 10 mas to reach the 0.1 kpc size scale at moderate redshifts.
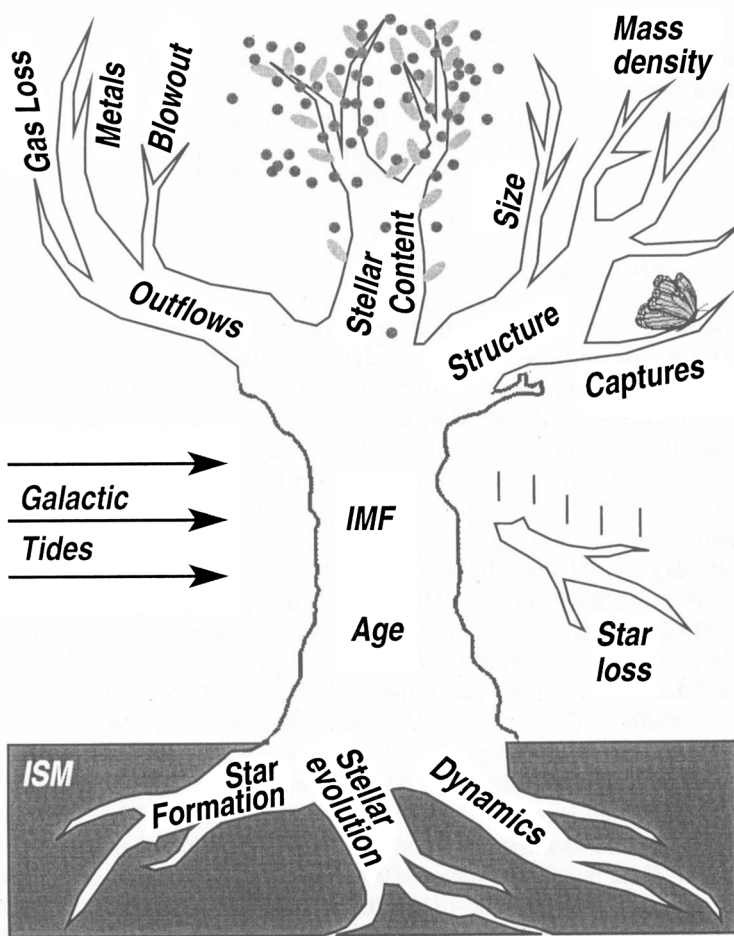
Figure 1. A cartoon illustration of some of the factors entering into the observable properties of star clusters.

This would allow us to distinguish individual luminous star clusters from their surroundings. Finally, sensitivity becomes a factor at large distances; e.g., an isolated young globular cluster will have K$\approx$ 29 mag at a redshift of z$\sim$5 (Burgarella, Chapelon, & Buat 1997).

Table 2.   Angular Resolution and Cluster Structures

Domain	Radius	0.1″ Scale	Results
Milky Way	250 kpc	≤ 0.1 pc	low mass stars
Local Group	$1 - 2$ Mpc	≤ 1 pc	luminous stars
Local Supercluster	~ 20 Mpc	≤ 10 pc	cluster structures
Universe nearby	≤ 500 Mpc	< 0.2 kpc	cluster census
High redshift	$z \geq 1$	~ 1 kpc	starburst clumps

3.   New Capabilities

We are benefiting from the continuing technological revolution in astronomy. Its components include high sensitivity multi-wavelength coverage; huge increases in effective area in the optical and infrared (OIR) from the construction of 6 to 10-m class telescopes on the ground and large area observatories in space, such as XMM; angular resolution gains from *HST*, Chandra in X-rays, ground-based adaptive optics, and radio interferometers; and tremendous strides in numerical modelling linked to advances in computing. All of these capabilities lead to better measurements of extragalactic clusters, as well as improved opportunities to quantitatively model their behavior.

So where do we go from here? Figure 2 illustrates some recent and planned observational capabilities in terms of wavelength coverage and angular resolution. For extragalactic star cluster research, where we need both sensitivity and angular resolution (e.g., super star clusters in NGC 1569: de Marchi et al. 1997; Hunter et al. 2000; Origlia et al. 2001; Maoz, Ho, & Sternberg 2001), the situation looks good across most of the spectrum. The exception is for improvements in far ultraviolet studies, where *HST* will continue to be the primary facility. While gains will be achieved in imaging from the Advanced Camera for Surveys in 2002 and from the Cosmic Origins Spectrograph (COS) in about 2004, this spectral region, that is critical for studies of youthful extragalactic star clusters in the nearby universe, may see little other improvement. Another concern is for future high angular resolution X-ray capabilities (see Fabbiano 2001).

4.   New Horizons

Formation of Massive Clusters. How star clusters, and especially dense, massive ones, form remains a problem. While progress has occurred in the development of basic theoretical ideas (e.g., Elmegreen & Efremov 1997; Nakasato, Mori, & Nomoto 2000; Klessen 2001), observations of super star clusters in formation do not exist. This issue is further complicated by the lack of even a basic theoretical model for the formation of high mass stars. Placing observational constraints on how massive stars (and their associated star clusters)
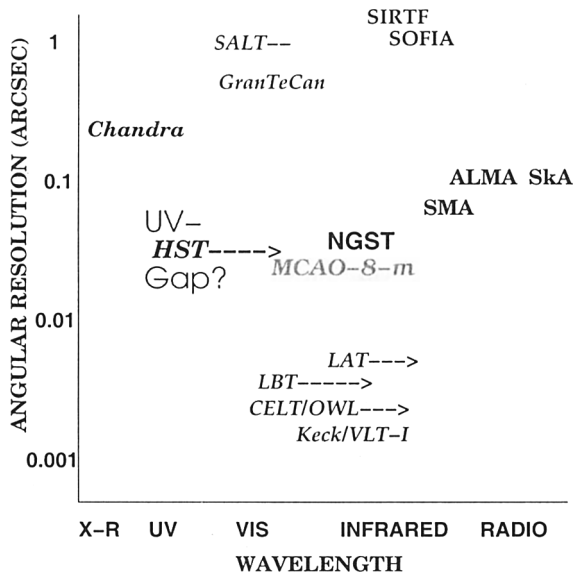
Figure 2.   A summary of some recent and planned observatories, whose capabilities can be applied to studies of extragalactic star clusters. These are discussed in §3 and §4 of this paper.

are made stands as a high observational priority for ALMA (e.g., Testi 2001), and for sub-mm measurements of the expected dusty cocoons surrounding the dense molecular cores where the cluster stars will condense (e.g., Motte & André 2001). Of course, very few, if any Galactic examples of massive young star clusters exist, and the work must be carried out in other galaxies. These offer the benefit of allowing the environments of young clusters to be mapped in straightforward ways. The combination of sensitivity and angular resolution offered by the Sub-Millimeter Array (SMA), now under construction in Hawaii, then offers substantial observational opportunities.

Impacts on the ISM. We are seeing progress in observing the emergence of massive young clusters from their natal gas. Centimeter wavelength radio continuum observations can detect the optically thick free-free emission from young, dense HII regions (Turner, Ho, & Beck 1998, Kobulnicky & Johnson 1999), and a wider range of radio techniques apply to the emission from warm molecular gas and likely presence of masers. With the substantial energy inputs from massive stars, FIR luminosities are sufficient to allow mapping studies (Gorjian, Turner, & Beck 2001). Youthful FIR-bright super star clusters could be charted in nearby galaxies with the modest angular resolutions of SOFIA and SIRTF. During this phase the molecular shells are shocked and bathed in FIR radiation, so masing can occur, opening additional observing strategies for radio interferometers (Baudry & Brouillet 1996, Plume et al. 1997). These will benefit from the increased capabilities of cm wavelength telescope arrays, such as the enhanced VLA project or future square kilometer array (SkA). In the later birth phases, the opacity of the molecular cocoon drops, and shorter wavelength

thermal IR and line emission (e.g., from shocked H_2 or H-Bracket recombination series) escapes. High angular resolution studies with future giant telescopes, such as the Large Atacama Telescope (LAT; 15-m class; 35 mas resolution at K with AO), the 30-m class California Extremely Large Telescope (CELT), or the even larger ESO 50–100 m OWL telescope hold great promise.

Once the young cluster is rid of its birth cloud, the ionization front powered by Lyman continuum radiation rapidly expands, leading to a giant HII region (or revitalizing one if already present), as in 30 Dor (but some giant HII regions, such as NGC 346 in the SMC, contain diffuse populations of OB stars). Due to their large sizes and high monochromatic brightnesses in H^+ recombination and forbidden emission lines, giant HII regions should be resolvable by a 6.5-m NGST throughout the visible universe. The bluest bright nebular emission line, [OII] $\lambda3727$, passes through the inner solar system minimum sky brightness region near 2 μm at z$\approx$5, which may represent a practical, but extremely interesting upper redshift limit for such studies.

Even before the ionization front breaks out from the molecular gas around a young star cluster, shocks associated with stellar winds will develop, and may produce X-rays from embedded star clusters (Hofner & Churchwell 1997). Later the colliding stellar winds themselves (Cantó, Raga, & Rodríguez 2000), as well as any high mass X-ray binaries (HMXRBs) [1], will join with supernovae to produce X-rays (Strickland & Stevens 1999; Fabbiano, Zezas, & Murray 2001; Yusef-Zadeh et al. 2001). UV metal resonance line absorption measurements (e.g., with *HST* + COS) offer the possibility to characterize the net wind from the cluster and its interaction with the surrounding ISM (Heckmann et al. 2001).

Cluster Structures. Structures are best derived by inverting maps of radial distributions of stars and their 3-dimensional velocities calculated from a combination of radial velocity and proper motion measurements. This process yields fundamental parameters, such as cluster dynamical masses and mass-to-light ratios, which tell us about the stellar mass functions (e.g., Sternberg 1998). New capabilities have allowed mass determinations for extragalactic star clusters from measurements of sizes on *HST* images and radial velocity dispersions observed with sensitive echelle spectrographs on large telescopes (Ho & Filippenko 1996; Dubath & Grillmair 1997; Larsen et al. 2001; Smith & Gallagher 2001).

These investigations can be extended if, for example, we gain the ability to measure proper motions with high precision in the Milky Way and its satellites via SIM or GAIA, or can do stellar kinematics with MCAO [2] feeding efficient spectrographs on very large telescopes. An MCAO-equipped 30-m telescope would allow exploration of the kinematics of individual pre-main sequence stars around young LMC clusters, permit radial velocity measurements to be routinely made for evolved stars in clusters within the Local Super Cluster, and extend routine internal velocity dispersion measurements to systems of clusters at D>100 Mpc.

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[1] Since many massive stars are in clusters for much of their lives, we may expect a correlation between HMXRBs and young super star clusters, although it is not clear if this is seen.

[2] Multi-conjugate adaptive optics (MCAO) opens the possibility of producing near diffraction-limited images in the near IR over moderate fields of view from large ground-based telescopes; see Rigaut et al. (1999).

Eventually the quest for better angular resolution will rely on interferometric techniques in the OIR, as well as throughout the radio. For example, the Large Binocular Telescope (LBT) provides 20 mas resolution at K-band from the interferometric focus of its two 8.4 m mirrors whose centers are separated by 14.4 m (Herbst et al. 2002). This resolving power in combination with its equivalent of 12-m collecting area is well-matched to half light radii measurements of compact star clusters throughout the Local Supercluster. The ambitious Keck and VLT interferometers hold the promise for order of magnitude better angular resolution, and when combined with sufficient sensitivity (a serious technical challenge!) could open a new field of *in situ* studies of young massive clusters at redshifts of z~1 (Gallagher & Tolstoy 1997).

Stellar Populations. Massive star clusters are the best representatives of "simple stellar populations" and provide fundamental tests of stellar evolution models and their offspring, the stellar population synthesis codes (see D'Antona 2002). These checks rest on our ability to measure color-magnitude diagrams, which are primarily a matter of combining sufficient resolution with photometric accuracy. This is difficult in cluster cores in the nearest galaxy, the LMC, even with *HST*; so we still have a ways to go. However, when multiple colors covering a wide wavelength baseline can be obtained, the statistics of cluster ages can be determined from their integrated broad-band colors, for example, by de Grijs, O'Connell, & Gallagher (2001) in M82.

A second technique relies on comparisons of synthetic and observed spectral energy distributions (e.g., González-Delgado, Leitherer, & Heckman 1999). This approach is ripe for exploitation with the advent of large format detectors coupled to multi-object and echelle spectrographs on high performance large telescopes. It will further benefit from the growth in numbers of 10-m aperture optical telescopes, such as the GranTeCan project, as well as the spectroscopically oriented Hobby-Eberly Telescope (HET), and its more UV-sensitive offspring, the Southern African Large Telescope (SALT), now under construction. Current studies have focused on determinations of ages and stellar luminosity (and thus mass) functions from optical spectra (e.g., Gallagher & Smith 1999,).

Since AO works best in the NIR, a new emphasis is being placed on the analysis of H- and K-band cluster spectra (e.g., Lançon et al. 1999; Alonso-Herrero, Ryden & Knapen 2000; Mengel et al. 2001). Ages of star clusters can be estimated from stellar absorption features in IR spectra especially by including the impact of the extended-AGB intermediate age stellar populations (see Lançon & Mouchine 2001). Still in its infancy but astrophysically critical is to derive ages *and* abundances from the integrated light of younger star clusters (Maraston et al. 2001). This exciting step would extend "Galactic" approaches for investigating the evolution of stellar populations to a variety of galaxies.

Disruption. We close our glimpse of the future by considering a nagging question: are massive young super star clusters analogous to common globular star clusters in their youth? The most direct way to resolve this issue would be to characterize youthful globular star clusters by observing them at high redshifts. Unfortunately, this is extremely difficult to do.

Conversely, we can ask if the massive young clusters we see today are likely to survive to ages of >8 – 12 Gyr? Then having resolved this basic point, we could turn to the more general problem emphasized by, among others, Fritze

v.-Alvensleben (1998), Whitmore et al. (1999), and Vesperini (2001): whether *systems* of young super star clusters would evolve to have the characteristics (e.g., luminosity function) of the populations of ancient globular clusters now seen in galaxies.

A difficulty with this approach is that the present-day globular cluster systems probably represent small fractions of initially much larger numbers of clusters, with many clusters having been lost through various destruction mechanisms (Gnedin & Ostriker 1997, Vesperini 2000). We are beginning to benefit from wide angle observations, which give quantitative insights into ongoing destruction processes (Odenkirchen et al. 2001; Siegel et al. 2001). More information will become available on Milky Way clusters from, for example, the Sloan Digital Sky Survey (SDSS), and with the added attraction of the Magellanic Clouds from the southern hemisphere Visible and Infrared Survey Telescope (VISTA), as well as from the NIR Primordial Explorer (PRIME) in space.

Further progress on the cluster survival issue comes from combining advances in theory and observations. Improved numerical models yield better information on the predicted behavior of massive clusters as they respond to internal effects, such as mass loss driven by stellar evolution and the formation and destruction of binary stars, as well as externally imposed dynamical constraints (Aarseth 1999; Kim, Morris, & Lee 1999; Fukushige & Heggie 2000; Giersz 2001 and references therein). A recent application of this approach to star clusters located near the center of the Milky Way shows that these objects cannot survive for long ($\ll 1$ Gyr) unless they are very massive (Kim et al. 2000; Portegies Zwart et al. 2001). Additional boundary conditions are imposed by the stellar mass functions; clusters with flatter mass functions are less likely to survive (e.g., Takahashi & Portegies Zwart 2000 and references therein). This could be an important factor since some star clusters in dense environments show signs of relatively flat stellar mass functions (Figer et al. 1999; Smith & Gallagher 2001), complicating the use of cluster luminosities to trace masses and thus destruction probabilities. Studies of intermediate age merger remnants, such as NGC 1316 by Goudfrooij et al. (2001), provide a critical link between the recent starbursts and the globulars, and give reassurance that some massive star clusters born in starbursts survive well into middle age.

It is definitely premature to consider this or many other fundamental issues regarding star clusters in our own and other galaxies as a closed subject. Rather this is an area where we may expect substantial progress in the coming years.

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