Scientific Requirements for Extremely Large Telescopes
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Exploring starburst astrophysics with ELTs

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Abstract. Star formation in starbursts produces compact star clusters which extend in mass up to the super star clusters (SSCs) which resemble young globular clusters. Compact young massive star clusters (cYMCs) in turn cluster along with other young stars into starburst clumps. Using M82 as an example we briefly review how the presence of starburst clumps affects the evolution of the host galaxy. Extremely large telescopes (ELTs) will be essential for understanding how starburst clumps and their constituent star clusters evolve. In nearby systems their combination of sensitivity and angular resolution will allow us to explore the structures, kinematics, and abundances of cYMCs. For systems at cosmological distances the high surface brightnesses of the starburst clumps makes them prime gateways for exploring the early evolution of galaxies.

Keywords. Galaxies: star clusters, evolution, starburst.

1. Introduction

The concept of starbursts developed slowly. The basic idea, that galaxies with rapid star formation could appear young due to the dominance of young stellar populations, was put forward by Sandage (1963) and thereafter was increasingly recognized to be a general phenomenon among galaxies (e.g., van den Bergh 1972, Searle *et al.* 1973). We briefly review characteristics of stellar populations in starbursts and then turn to discussing opportunities that could be offered by new generations of extremely large telescopes (ELTs; optical-infrared (O-IR) telescopes with apertures of 20-m to 100-m).

2. M82: Exploring a clumpy starburst

The unusual structure of M82 (D=3.6 Mpc; 1 arcsec=17.5 pc) is immediately clear from ground-based images. The inner part of M82 is dominated by several bright clumps, which are crossed by the famous dust lanes. This region also contains concentrations of bright star-like objects. Early studies suggested these were compact star clusters. This was confirmed by HST imaging that also showed the bright clumps to consist of closely packed star clusters (O'Connell *et al.* 1995, Melo *et al.* 2005).

M82 further stands out due to gas concentrations in its center and surrounding the galaxy (Yun *et al.* 1993). The external gas and large ISM concentration in the central region of M82 are thought to be products of a recent interaction with the M81 spiral galaxy. The starburst occurred when a rapid influx of gas ignited an epoch of intense star formation. M82 provides a prime example of feedback in action. Young stars are very centrally concentrated so M82's inner stellar density must increase, but young stars also drive a galactic wind that sends a significant fraction of the gas back into to the surrounding space. The postburst system could have lower total central mass densities than exist at present. The fate of the ejected gas remains a critical but unanswered aspect of galaxy evolution (see Martin 2005).

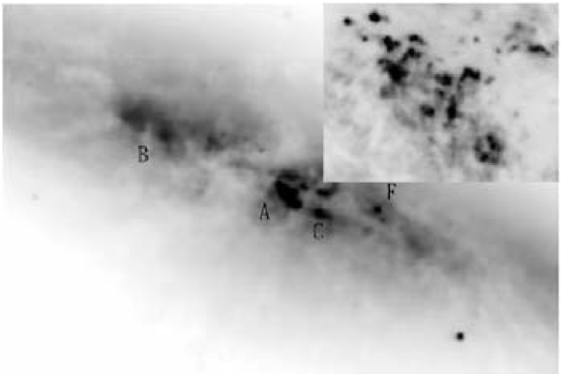

Figure 1. An R-band image of the central regions of M82 from the WIYN 3.5-m telescope in $\sim$1 arcsec seeing shows its unusual starburst clump structure. Major clumps A, B, and C are labeled, as is SSC M82-F. The inset presents a closer view of M82-A from an HST- WFPC2 F555W filter image that reveals some of the embedded cYMCs (see Melo *et al.* 2005).

2.1. *Evolution of the young star clusters*

Populations of cYMCs and their more massive cousins, the SSCs, opens a new path for studying starburst galaxy evolution. Star clusters are simple stellar populations, SSPs, consisting of stars of one age and metallicity; they follow on from massive stars as tracers of the evolution of stellar populations. Many cYMCs are >100 times more luminous than supergiant stars and yet are long lived. They also are compact, with half light diameters of 5-10 pc, and effectively "star-like," i.e. have very high surface brightnesses and will be unresolved in distant galaxies. Given that globular clusters must descend from massive, compact star clusters which formed at very early epochs, SSCs could be powerful cosmological probes for telescopes with sufficient angular resolution and light collecting area.

Age is a key parameter of cYMC populations. It can be obtained from multi-band photometry (Anders *et al.* 2004), or with better reliability, via more costly spectroscopy. Examples of the latter approach include optical spectroscopy of the M82 cluster populations, but even in M82 spectra of the critical Balmer jump region are available only for M82-F (Gallagher & Smith 1999) and M82-A1 (Smith *et al.* 2006).

Unfortunately, the evolution of star cluster populations depends on several factors, many of which are not easily observed. Thus it is difficult to go from numbers of older star clusters to a star formation rate (SFR). Additional complications could arise from the close spatial packing of stars within massive SSCs; e.g. intense UV radiation from hot main sequence stars might affect the outer atmospheres and thus spectra of RSG or AGB stars in clusters with ages of <1Gyr.

Integrated light velocity dispersion measurements exist for several nearby SSCs (Ho & Filippenko 1996a,b, Larsen *et al.* 2001, Smith & Gallagher 2001, McCrady *et al.* 2003, Maraston *et al.* 2004). These are made in the red or near IR where cool stars with intrinsically narrow absorption lines dominate the light. Internal dispersions are about $\sim$8-15 km s^{-1} for typical SSCs. Half light radii thus far come only from HST imaging and are 2-10 pc, yielding masses of 10^5 to 10^6 $M_\odot$. Empirically determined mass-to-light ratios vary relative to predictions from fixed IMF SSP models with the same ages. This apparent range in stellar mass functions could arise from several factors, including mass models for the clusters, effects of mass segregation, or intrinsic variance in the stellar IMF.

Uncertainties in the stellar mass distributions and problems in assessing structures complicate theoretically predictions of cYMCs' long term stability (e.g. Smith & Gallagher 2001, McCrady *et al.* 2005). Empirical studies, however, suggest low survival rates for young massive clusters. A large fraction of cYMCs apparently dissolve quickly, within 10-30Myr (Tremonti *et al.* 2001, Fall *et al.* 2005), while the remaining population thins more slowly (Bastian *et al.* 2005, Lamers *et al.* 2005). Thus the numbers of star clusters of a given age reflects the balance between birth and destruction rates, and a simple census does not yield cluster formation rates for times beyond ~30Myr, let alone historical SFRs.

This complicates determining whether SSCs are younger versions of globular star clusters (Ashman & Zepf 2001). Their masses, sizes, and velocity dispersions favor this view. The small numbers of intermediate age systems of compact massive star clusters, however, imply very low survival rates, and indeed we have found few systems of massive compact star clusters with intermediate ages of about 4-8Gyr. Yet if the SSC birth rate tracks the mean cosmic SFR density, and we expect that SSC formation is favored when star formation is intense, then we still might find significant numbers of intermediate age compact clusters from the high SFR epochs at $z > 1$, corresponding to ages of >6Gyr. The observed preponderance of old globular star clusters, independent of the mean stellar population age of the host galaxy, suggests that ancient cYMCs/SSCs could have been particularly durable.

2.2. *cYMCs and starburst clumps in M82*

M82 provides the best setting for observing the properties of populations of YMCs and SSCs. The young examples of these star clusters with ages of <30Myr are mainly but not entirely concentrated in 'starburst clumps'. These are regions of active recent star formation with sizes of 100-300pc, within which are tightly packed with cYMCs. The SSC M82-A1 is relatively isolated and could be studied with a combination of HST imaging and STIS spectroscopy (Smith *et al.* 2006). Its properties are typical of an M82 SSC, but surprisingly, despite its ~7Myr age, M82-A1 is surrounded by a compact (R=5pc) H II region. A clue to how such a feature could survive around a $\sim 10^6 M_\odot$ cluster that should have produced supernovae comes from the high ISM pressure of $P/k \approx 10^7$ measured from the strengths of the nebular [SII] emission line doublet. This is ~100 times the ISM pressure locally in the Milky Way and suffices to stall the stellar winds and initial supernova ejecta from M82-A1. The high ISM pressure is supplied by hot gas (kT ~ 0.7-0.9kev) that pervades the region around the main starburst clumps. The structure of the ISM in M82 thus is quite different from that in the Milky Way's disk (see also Förster-Schreiber *et al.* 2001, 2003).

Chemical abundances for the M82 ISM estimated from the nebular emission line gives a solar value for oxygen (Smith *et al.* 2006). Hayashi tracks set lower bounds on the temperatures of convective stars and thus young SSCs have H-band spectra close to that of a single red supergiant star. This can be exploited to determine abundances; Origlia *et al.* (2004) find a near solar iron abundance along and enhancements of light α-elements in M82 clusters, consistent with the X-ray spectra of the hot gas.

2.3. *Superwind*

M82 has a well known galactic superwind. The wind shows up across the spectrum but the interpretation of its structure is complicated by the presence of circumgalactic cool gas, a remnant of the last interaction with M81 (Yun *et al.* 1993). While modified versions of dominant central wind models reproduce the features of the M82 wind (Shopbell & Bland-Hawthorn 1998; Ohyama *et al.* 2002), our combined HST and WIYN telescope

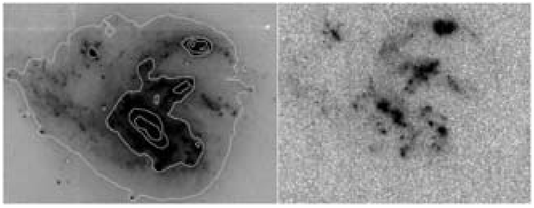

Figure 2. HST-WFPC2 images of NGC 7673 in the visual (F555W filter, left) and Near-UV (F280W filter, right) from Homeier *et al.* (2002) provide a nearby illustration of the multiwavelength dominance of starburst clump structures.

ground-based images suggest the wind currently comes from the individual starburst clumps (Gallagher *et al.* 2006). This model implies: (1) Injection of mass into the wind is not steady but evolves on the 30-40Myr time scales for SNe II production. (2) Wind collimation occurs locally within the clumps and in some cases via interactions between YMCs (Tenorio-Tagle *et al.* 2003). This increases the ratio of hot wind-warm/cool ISM interfaces, facilitating mass loading of the wind. (3) Locations of the wind and OB stars are correlated. If we viewed M82 from above we would see very pronounced outflow features in the integrated UV spectrum. In calculating mass loss rates from observed gas column densities, we should use the covering area of the clumps, not that of the entire galaxy.

3. Implications for the starburst mode of galaxy evolution

The presence of starburst clumps is connected to galaxies with large amounts of gas. Theoretical models by, for example, Noguchi (1999) and Immeli *et al.* (2004) show that clumps form when gas rich galactic disks become locally unstable and form gravitationally bound subsystems. This behavior was initially studied by J. Heidmann and collaborators (e.g. Casini & Heidmann 1976), who noted the connection between nearby galaxies with clump-dominated structures and high SFRs.

NGC 7673 is a nearby example of this phenomenon (Figure 2). As in M82, the NGC 7673 starburst clumps contain many YMCs, thus M82 is an archetype for this mode of star formation. Going beyond the local universe, galaxies with clumpy morphologies become increasingly common at higher redshifts (Elmegreen & Elmegreen 2005); e.g. a gravitationally lensed galaxy with $z = 4.92$ whose image was reconstructed with about 2 kpc resolution by Franx *et al.* (1997) resembles a typical clumpy starburst system. Whether the similarities in morphologies between high redshift objects and local clumpy starbursts translate into similar physical circumstances remains to be seen.

4. Opportunities for Extremely Large Telescopes

We assume D=30-m ELT with excellent natural seeing for λ <800 nm, a reasonable Strehl AO for H-band and beyond, and basic instruments. A variety of natural limits also must be taken into account. For example, the JHK-band composite spectra of SSCs contain little age information (see, e.g., Mouchine & Lançon 2002, Förster-Schreiber *et al.* 2003). Effective use of such an expensive facility further imposes a need to make good use of *all* the observing time, including those when conditions are worse than the median and faint object AO is not effective.

The conservation of intensity in a diffraction-limited case also places fundamental limits on spectroscopy. A source with constant photon intensity $I_0(\lambda)$ over a solid angle that is significantly larger than the diffraction limit produces a flux per resolution element that scales as $I_0(\lambda)\lambda^2$, independent of aperture, and generally is not adequate for faint object spectroscopy. A rough calculation gives signal-to-noise of >8–10 per hour per resolution element in the sky background between OH lines only for spectra with $R < 1000$. Spectroscopic systems that allow the diffraction solid angle elements to be coadded, such as IFUs, will be needed for many projects.

ELTs would advance our knowledge of the astrophysics of starbursts and intense star formation in a number of ways. A more thorough development would include the properties of embedded SSCs from their thermal infrared, relationships to galaxy nuclei, kinematics of young star cluster systems in recent mergers, and the dynamics of different stellar mass components from studies of cYMCs such as Westerlund 1 in the Milky Way. In these programs ELTs will provide key pieces of information, but they will not do the whole job. Specialized O-IR capabilities such as those of SIM in space and O-IR interferometers on the ground also are necessary, as are complementary multiwavelength observatories. The opportunity to use O-IR interferometers to investigate the detailed structures of extragalactic cYMCs from birth through the beginnings of their dynamical dissolution particularly merits tradeoff studies versus what should be done with ELTs (e.g. Gallagher & Tolstoy 1997).

- **Structures of SSCs:** The ≈17 milliarcsec angular resolution and symmetric core PSF of a 30-m ELT in the H- and K-bands is a factor of 3 improvement in resolution over HST. This and a 10-fold increase in collecting area opens the way for systematic studies of sizes, masses, kinematics, and chemical abundances of SSCs throughout the Local Supercluster, e.g. in the Antennae. The use of IFUs to obtain spectroscopic images will offer a powerful way to separate cYMCs from the background by their velocities as well intensity profiles. The use of AO on an ELT will foster high spectral resolution studies yielding more and better chemical abundances while also enabling surveys of internal velocity dispersions for large samples of clusters of varying age. Outcomes will include comprehensive stellar abundance determinations for a range of starbursts, and understanding how present day stellar mass functions and structures of cYMCs influence survival rates and relationships to globular star clusters.

Taking full advantage of the opportunities opened by AO on ELTs in the near infrared will require continued preparatory work on infrared properties of stellar populations covering a range in age. Much of the necessary data can be obtained in the Local Group using existing telescopes, providing an excellent starting point for spectroscopic surveys of key infrared spectroscopic characteristics of SSPs and composite stellar populations (Förster-Schreiber *et al.* 2001, 2003, Lançon & Mouchine 2002).

- **ISM feedback:** Studies of nearby starbursts in the light of emission lines ranging from [Fe II] in PDRs, H-recombination, He I, [Ne II], and [S III] in ionized gas will open new avenues for charting the impact of cYMCs/SSCs on the surrounding ISM at angular scales well below what has been achieved with HST. Narrow band imaging would concentrate on the structures of interfaces, such as photoionized cloud surfaces and shocks associated with galactic winds, as well as the nebulae associated with cYMCs. Adding imaging spectroscopy to the mix adds the ability to determine velocity fields and dispersions, keys to testing predictions of feedback models especially with regard to mass loading and entrainment.
- **Clump structures:** Starburst clumps are the highest surface brightness large scale features in the disks of galaxies. Thus clumps are prime targets for exploring the evolution of massive galaxies in the high SFR phase of their evolution that was common at $z > 1$. Large clumps in young galaxies seen at moderately high redshifts will be near the resolution limit of a 30-m ELT in the H-band, and observing them would open the way

for extensive quantitative studies of star forming properties *within* young galaxies that can be compared to those of the local standards. For example, position-velocity studies might allow us to determine whether we are dealing with starburst disk geometries that are prevalent nearby, or the possibility of starburst clumps arrayed in three dimensions in galaxies which are rapidly accreting gas from their surroundings.

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Discussion

PUZIA: What is the mass fraction of the M82 starburst? To what kind of galaxy would M82 evolve if left undisturbed?

GALLAGHER: The mass fraction of the current starburst is not all that large - probably $< 10\%$. However, the galaxy is very centrally concentrated in mass, e.g. the inner rotation curve appears to rise rapidly. So much of the total stellar mass may have formed in episodic starbursts associated with close passages by M81, or certainly $\sim 1/2$ of the stellar mass in the central regions. The fate of M82? If undisturbed it may become a NGC 5102 or other peculiar S0 system. But it will be disturbed by future M81 passages, and so may eventually be tidally stripped and end up as an M32-like dense compact galaxy.

ZINNECKER: I am particularly interested in your compact cluster M82-F with evidence from M/L for an abnormal (top-heavy) mass function. Can you tweak the parameters in ways such as to save the low-mass stars and hence the possibility for this cluster to ultimately become a globular cluster?

GALLAGHER: An interesting possibility that we should explore. We were conservative, but then ended up with a very short present day mass spectrum. It would be a good idea to ask how much mass would be allowed in the form of low mass stars if one is allowed to adopt an unconventional stellar PDMF.

OLSEN: Could M82 be forming OB associations and dissolving them too quickly to detect, or is the formation of pre-association clamps being disrupted? (Second part not asked in session: Is the number of stars M82 could form in disrupted associations too unimportant to consider?)

GALLAGHER: Possibly. This issue is observationally difficult as the clumps contain sheets of moderate density OB stars. These could mask normal OB associations. We do see a few examples of objects that resemble scaled OB associations in M82. If the lifetime of normal OB associations is short, then they will be hard to find on images. Even so we then should be able to find spectroscopic signatures of young OB stars in the diffuse light.

DAVIDGE: One of the key issues that ELT SACs must consider is wavelength coverage. You mentioned the need for spectroscopy in the thermal IR. Do you mean 3-5 μm or 8–25 μm, or both? How would you rank those as diagnostics?

GALLAGHER: Both would be useful. For example, high angular resolution studies of [NeII] are valuable for studies of inner regions. The 25μ window is maybe our best bet to find superstar clusters emerging from their cocoons. The 3.5μ window has been used to find hot dust and also some key emission lines. This order is a guess at the rankings. On the other side access to 0.8μ is important for age determinations from the strengths of higher Paschen series absorption lines.