Star Formation's Dependence on Environment

A Working Paper for the Astro2010 Survey
PSF and GAN Science Panels

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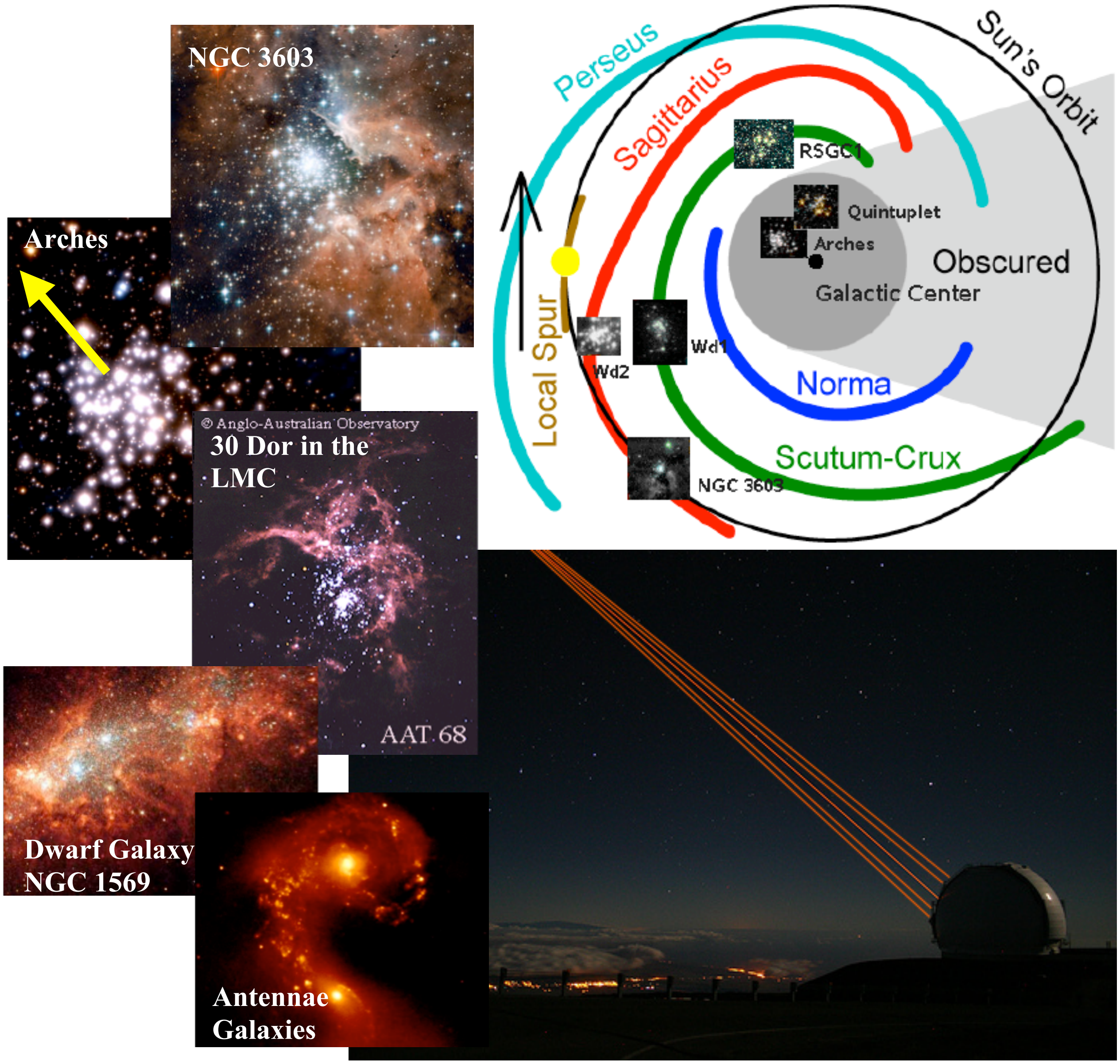

Reprinted images of massive young star clusters including the Arches (Stolte et al. 2005), NGC 3603 (Hubble Hertiage Project), and 30 Doradus in the LMC (Malin and the Anglo-Australian Observatory). Images of galaxies include NGC 1569 (P. Anders, NASA/ESA) and the Antennae (B. Brandl, WIRC team, Cornell/Palomar). Additional images are from Brandner 2008 (top right) and simulated with lasers from a photo of the Keck II telescope (bottom).

Introduction

Our view of the cosmos is primarily illuminated by starlight. Thus, the formation of stars is perhaps one of the most important astrophysical processes in the universe. Star formation affects the formation and evolution of galaxies, enriches and regulates interstellar gas, and gives rise to planetary systems. Despite the fundamental importance of star formation, physical still struggle with simple questions such as whether the star formation process is universal or varies with environment and what physical conditions determine the numbers and relative proportions of low and high mass stars that are formed.

Conceptually, star formation is simply a competition between gravity and supporting pressure forces in dense gas. However, accurate calculation of the star formation process is made difficult by several factors. First, the initial conditions for star formation are still uncertain. Second, the process depends on physical conditions over a wide range of temporal and spatial scales, which leads to nonlinear behaviors that are difficult to model. And, thirdly, there are a variety of poorly understood physical processes that support the gas against gravitational collapse such as thermal pressure, magnetic fields, turbulence, and stellar feedback. A successful theory of star formation should be able to predict the observed numbers and masses of stars formed over a large range of physical scales and for a variety of gas conditions. This includes scales relevant to galaxies (e.g. the Kennicutt-Schmidt relation showing a correlation between star formation and gas surface densities), giant molecular clouds, star clusters, and individual pre-stellar cores. The key observables predicted by such a theory would also include the timescale of star formation in these systems, the total star formation efficiency, the initial cluster mass function (ICMF), the stellar initial mass function (IMF), and multiplicity and kinematic properties of the stars. At this time, we are a long way from having such a complete theory of star formation (McKee & Ostriker 2007) due to limited observations constraining the initial conditions, conflicting results on IMFs observed in nearby star clusters, and the limited conditions in which star formation has been observed so far.

In this paper we discuss two areas in which we expect progress to be made in the next decade and beyond. First, measuring star formation rates and the initial cluster mass functions for a large set of galaxies will address the question of whether the star formation process is universal or varies on cosmological scales. Although star formation cannot be observed with the same level of detail as in our own Galaxy, other galaxies provide a broader range of environments including gas-rich starburst galaxies, merging galaxies, and galaxies with high/low mass or metallicity. Second, precise measurements of initial mass functions for individual star clusters in both *normal* and *extreme* environments within the Milky Way, LMC, and SMC will allow us to determine if and how the star formation process varies with the physical conditions of the gas. While current studies of nearby star forming regions provide many constraints for star formation theories, observations need to be extended to a broader range of environments such as more distant very massive star clusters, clusters in the Galactic Center, and clusters in low metallicity environments such as the Large and Small Magellanic Clouds. Improved understanding of very massive star clusters ($>10^4$ M_{sun}) is particularly important as these rare clusters contribute just as much or more stellar mass and energy to the Galaxy as all Taurus-like and Orion-like clusters (Lada & Lada 2003). Observational and theoretical work on both galactic and extragalactic fronts will eventually overlap in terms of cluster mass and gas conditions. And this will provide a missing link between our understanding of star formation from familiar regions such as Taurus and Orion and our view of star formation from super star clusters and integrated stellar populations seen in other galaxies.

Star Formation Rates and the ICMF in Different Galactic Environments

In the last decade we have moved from globally averaged studies of star formation rates for whole galaxies and circumnuclear starbursts (e.g. Kennicutt 1998) to spatially resolved studies on sub-kiloparsec scales for nearby galaxies (e.g. Leroy et al. 2008). Despite these improvements, most studies of star formation in other galaxies are still unable to detect individual star clusters below ~10^5 M_{sun}. This limits the comparisons that can be made to massive young star clusters in the Milky Way or the LMC, which only reach 10^4 M_{sun} (Figure 1). Pushing to even smaller angular scales in galaxies at distances of ~10 Mpc (where 5 pc spans 0."1 on the sky) will enable studies of individual giant molecular clouds and star clusters at sizes and scales comparable to the well-studied clouds and clusters within the Milky Way. With such observations, the initial cluster mass function can be determined for galaxies of quite different environments: quiescent and starburst galaxies, isolated and merging galaxies, large spirals and dwarf spheroidal galaxies. Even for more distant galaxies at higher redshift, improved spatial resolution will enable detailed comparisons on ~100 pc scales of star formation rates with the distribution and properties of gas.

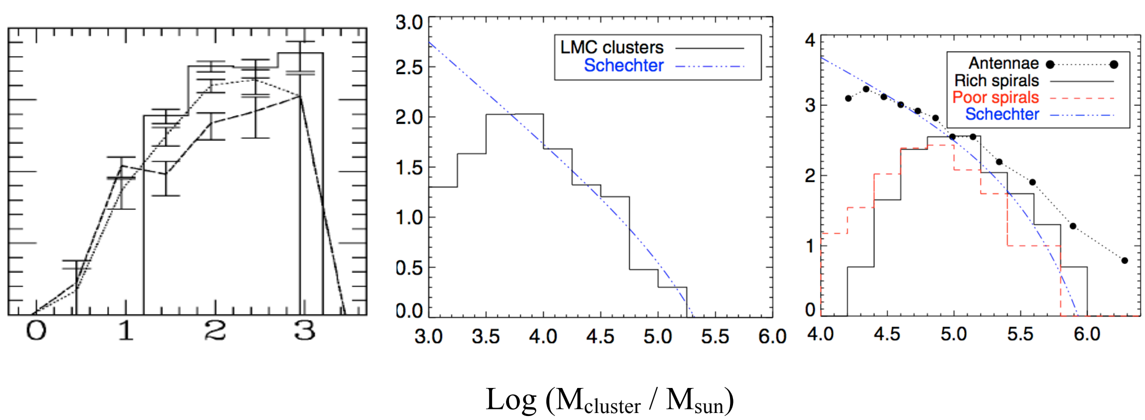

Figure 1: Observed cluster mass functions for young clusters in the Milky Way (left), the LMC (middle), and other nearby spiral galaxies (right). Each panel shows a log-log plot of the number of clusters at a given mass. However, the range of cluster masses is quite different in the three panels, making comparison difficult. The Milky Way's ICMF (left) is reprinted from Lada & Lada 2003 and the LMC's and nearby spiral galaxies' ICMF (middle) are reprinted from Larsen 2009. Further observations of high mass clusters in the Milky Way and low mass clusters in other galaxies are needed to probe whether cluster formation depends on environment.

The ICMF provides a critical link between star formation and galactic structure formation. The majority of stars form in clusters and associations (Lada & Lada 2003). Over time, various internal and external processes act to disrupt the clusters and disperse their member stars. There is growing observational evidence that the removal of residual natal gas causes a large fraction of clusters to dissolve within the first 10 Myr after birth (Goodwin & Bastian 2006); but, theory suggests that the fraction of stars that remain in bound clusters after this time is a sensitive function of the star formation efficiency and the time scale over which the gas is removed (Baumgardt & Kroupa 2007). Measuring the cluster mass fraction as a function of age in different environments therefore holds the promise of revealing how these quantities vary with environment. Theory also suggests that the distinct structures of the Milky Way, including the thick and thin disks (Kroupa 2002) as well as the spheroidal halo (Kroupa & Boily 2002), may have formed as the result of the disruption of distinct populations of star clusters formed early in the history of the Galaxy. Conditions in the early history of the Galaxy, as well as conditions observed at high redshift today, were substantially different than present conditions in the local universe. The extreme environments of starburst galaxies, merging and interacting galaxies, and the Galactic Center offer present-day analogs to the conditions prevalent in the early universe. Young massive star clusters are ubiquitous in these extreme environments. High spatial resolution observations of the ICMF as a function of age provide evidence as to how these cluster populations form, how they are destroyed, and how their stars contribute to the distinct stellar populations associated with the structural components of disk galaxies.

Another major goal for the study of star formation in other galaxies is to compare the amount and types of stars that are formed to the amount and properties of the gas. Therefore, multi-wavelength studies are essential to probe the atomic, molecular and ionized gas, and the embedded and revealed stellar populations. The facilities that will enable this observational progress include the James Webb Space Telescope (JWST), the Atacama Large Millimeter Array (ALMA), the Square Kilometer Array (SKA) and new large ground-based optical and IR telescopes. While JWST will have dramatically improved sensitivity in the near and mid infrared compared with existing capabilities, only 30 m ground-based optical/IR telescopes equipped with adaptive optics can provide sufficient angular resolution to detect Orion-sized star clusters in many other galaxies.

A 30 m diameter telescope with adaptive optics will have angular resolution of 0."006 and 0."017 at 0.67 (H-alpha) and 2.0 microns, i.e. resolving scales <~1 pc at 10Mpc, i.e. the scales of individual star clusters (see Figure 2, Table 1). Thus, an achievable objective in the next decade is to resolve the bulk of star formation activity in a large (~100) sample of nearby (~10 Mpc) galaxies into individual young stellar clusters. Such a study will simultaneously address the causes of galactic scale star formation rates and the physics of star cluster formation, for example by looking for variations in the ICMF with metallicity, orbital shear, and location relative to spiral arms. Current studies of this question are typically limited to scales of 10's of pc in the nearest galaxies, more relevant to OB associations rather than individual star clusters (e.g. Dowell et al. 2008). Spectroscopy of such clusters is critical to determine ages and dynamical masses. Measurements of the dynamical masses of individual clusters require high spectral resolution (R~20,000) and high spatial resolution and they yield constraints on the mass to light ratio and the IMF of the cluster (e.g. McCrady et al. 2003). Furthermore, the improved angular resolution of a 30 m telescope will probe the high-mass end of the cluster mass function even in far more distant galaxies. Pushing studies of star and cluster formation to larger distances will enable us to measure the properties of star formation in galactic environments that are quite rare locally but were the dominant types of star forming galaxies at earlier cosmic times.

Figure 2: Figure reprinted from Zinnecker and Yorke 2007 showing a 30" (7.5 pc) optical/IR image of R136/30Dor, a dense massive (~10^5 M_{sun}) young cluster in the LMC. The inserts simulate what *(a)* NGC 3603 (~10^4 M_{sun}) and *(b)* Orion (~10^3 M_{sun}) would look like at the same LMC distance with HST resolution. Ground-based 30 m telescopes equipped with adaptive optics systems will offer at least a factor of 10 improvement in spatial resolution over HST. This will allow individual Orion-like clusters to be resolved in galaxies out to 10-20 Mpc. Studies of clusters over a range of masses in a range of galaxy types will determine if and how the initial cluster mass function (ICMF) varies with environment.

Dependence of the IMF on Properties of the Host Star Cluster and Galaxy

The stellar initial mass function (IMF) is a key observable for constraining theories of star formation and influences the rate of metal enrichment and feedback into the surrounding ISM. Additionally, knowledge of the IMF, its origin, and its evolution are critical to the interpretation of observations of distant galaxies and galaxy evolution. There are numerous extragalactic integrated-light studies that invoke IMF variations with environment or redshift to explain otherwise discrepant observations (e.g. Hopkins & Beacom 2006, Van Dokkum 2008). Locally, there is evidence that the IMF differs between nearby star forming regions, such as Taurus or Orion, and some massive star clusters where individual stars can be resolved (e.g. Mengel 2002, Stolte et al. 2005, Harayama et al. 2008). However, alternative analyses of the same cluster can produce different IMFs such as for R136 in the Large Magellanic Cloud (Brandl et al. 1996, Massey & Hunter 1998). Furthermore, the apparent variations in the IMF still have large uncertainties and may be attributable to the random statistical sampling of a universal IMF (Elmegreen 2009). These discrepancies have fueled the debate as to whether or not there is a universal IMF and whether extreme environments and conditions change how star formation proceeds. On the theoretical side, models have been advanced in which the IMF is expected to vary with the density of the environment (Krumholz & McKee 2008), with the mass of the parent cluster (Bonnell et al. 2004), or essentially not at all (Elmegreen et al. 2008). Each of these predictions is based on emphasizing different physical processes in the star formation process (radiation feedback, competitive accretion, and the thermal properties of ISM gas, respectively). Determining which, if any, matches the observed variation of the IMF would provide a vital clue to the physics of star formation.

The universality of the stellar IMF can be assessed by precisely determining the contents of young stellar clusters in a range of environments, including the low-metallicity of the Large and Small Magellanic Clouds (LMC & SMC), the high shear environments of the Galactic Center, and the high crowding and high pressure environments at the cores of super star clusters and the Galactic Center. Star clusters in such environments are ideal laboratories for probing the IMF as they represent a roughly coeval population located at a uniform distance. One major observational limitation is that clusters in these environments are also very crowded (Table 1). Resolving and detecting the individual high and low mass members of clusters in these extreme environments requires near-IR diffraction limited imaging from JWST, 8-10 m telescopes, and 30 m telescopes. JWST's spatial resolution of 0."08 will resolve individual stars only for the outskirts of the closest and least-dense clusters. Existing 8–10 m class telescopes (0."05 resolution) will require upgraded wide-field adaptive optics (AO) systems, such as the planned Gemini Multi-Conjugate AO or the Keck Next Generation AO systems, in order to cover the large angular extent of galactic star clusters (~1 arcmin) and to resolve individual stars in more distant clusters in the Galaxy. However, a 30 m telescope, with an AO system providing 0."015 resolution, is required to detect individual stars down to low masses in the cores of the most massive Galactic star clusters (e.g. Arches, Westerlund 1) and clusters in the LMC or SMC.

Table 1: Cluster properties in the Galactic Center, LMC and M82

Distance (kpc)	**Cluster Size** (1pc diameter) (arcsec)	**Star Separation in Core** (arcsec) (based on ONC Trapezium)	**Proper Motion for 10 km/s** (mas/yr)	**Typical Binary Separation** (~30AU) (mas)	**Hydrogen Burning Limit** (K mag)
8 (GC)	25.8	0.13	0.264	3.76	19
60 (LMC)	3.44	0.02	0.035	0.50	23.5
3500 (M82)	0.06	3×10^{-4}	6×10^{-4}	9×10^{-3}	32

The basic method for determining IMFs involves measuring the NIR fluxes of a resolved stellar population, constructing the luminosity functions (including estimates of reddening) and then comparing to theoretical models of pre-main-sequence evolution of a cluster, for which the IMF is one of the main input parameters to be constrained (Muench et al. 2002). Current results on IMFs in nearby massive star clusters are limited by an inability to determine cluster membership due to contamination by background stars and variable extinction. Proper motions can solve this problem as has already been demonstrated for fast moving globular clusters (Figure 3) and Galactic Center clusters such as the Arches (Stolte et al. 2008) with astrometric precisions of ~1 mas. Proper motion measurements of massive star clusters in the Galactic disk and in the LMC require near-IR astrometric precisions of ~0.05 mas, which will be achievable with adaptive optics equipped 30 m telescopes.

IMF estimates can be further refined by measuring stellar temperatures from NIR spectra and constructing HR diagrams for clusters, which can then be compared to theoretical models (e.g. Palla & Stahler 1990; Baraffe et al. 1998; Chabrier et al. 2000). This technique has been demonstrated for a number of nearby or low mass clusters (e.g. Hanson et al. 1996 for OB stars; Meyer 1996 for A-K stars; Luhman et al. 2005 who used R=1000 spectra to estimate spectral classes to ±1 subclasses for M types). Similar observations of massive star clusters at higher stellar densities and larger distances requires sensitive integral-field or multi-object spectrographs with R~4000 on 30-m telescopes equipped with adaptive optics.

Studies described above will constrain star formation theories in a number of other ways in addition to the stellar IMF. Proper motions will enable the study of clusters' internal kinematics. These can be used to derive dynamical cluster masses, probe the dynamical evolution and survival times of clusters, and, in conjunction with ALMA, investigate the kinematic relationships between stars and gas at early ages. This relationship is a particularly important discriminator between different theoretical models for the origin of the IMF (Krumholz et al. 2005, Bonnell & Bate 2006). High spatial resolution mid-IR and X-ray observations can also be used to measure the impact of environment on disk evolution and accretion onto individual young stars. X-rays are also a promising way of searching for embedded low mass stars in the vicinity of massive ones, since the contrast ratio in x-rays is much smaller than at visible or IR wavelengths (Feigelson et al. 2007). X-ray observations may therefore make it possible to study stellar mass functions in the immediate vicinity of massive stars, thereby determining how those stars affect the formation of their less massive neighbors.

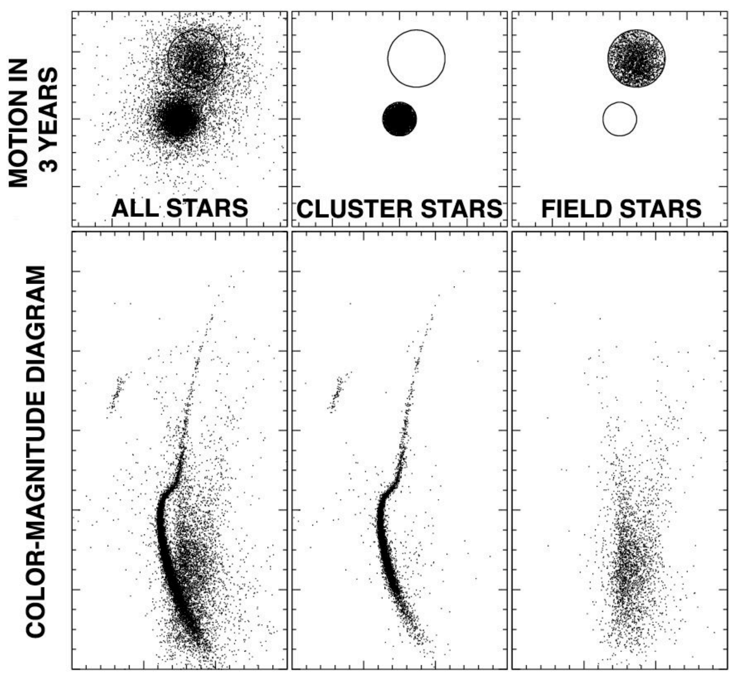

Figure 3: Astrometric precisions achievable with adaptive optics systems on ground-based 20-30 m telescopes can effectively identify cluster members based on their peculiar motions. This figure is reproduced from Anderson et al. (2006, Fig. 11) and shows the peculiar motion color-magnitude diagrams for optical images of a globular cluster with all stars, cluster stars, and field stars. Higher precision, near-IR astrometric capabilities will yield similar results on young massive star clusters throughout our Galaxy and in the low-metallicity environments of the LMC and SMC.

Programmatic Recommendations

In addition to ALMA and JWST, a large (~30m) diameter optical/NIR telescope equipped with adaptive optics is the primary recommendation to advance observational studies of star formation. Adequate support for instrumentation is essential to exploit the capabilities of such a telescope. The adaptive optics systems should provide wide field-of-view imaging capabilities with uniform correction over the field of view in order to maximize the efficiency for observing Galactic star clusters than subtend ~1' on the sky. Moderate resolution (R~4,000) spectroscopy in integral field or multi-object infrared spectro-graphs are necessary for deriving mass functions and cluster ages. An instrument with multi-object high spectral resolution (R~20,000) capabilities would be ideal for deriving virial masses and IMF constraints on extragalactic star clusters. Studies of star cluster formation in external galaxies and the stellar IMF in star clusters in the Milky Way, LMC, and SMC will benefit from high quality NIR imagers and NIR multi-object or integral field spectrographs. This facility will strongly complement ALMA and JWST.

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