The Magellanic System: Stars, Gas, and Galaxies
Proceedings IAU Symposium No. 256, 2008
Jacco Th. van Loon & Joana M. Oliveira, eds.

doi:10.1017/S1743921308028512

Time resolved star formation in the SMC: the youngest star clusters

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Abstract. The two young clusters NGC 346 and NGC 602 in the Small Magellanic Cloud provide us with the opportunity to study and the efficiency of feedback mechanism at low metallicity, as well as the impact of local and global conditions in cluster formation and evolution. I describe the latest results from a multi-wavelength, large-scale study of these two clusters. *HST*/ACS images reveal that the clusters have very different structures: NGC 346 is composed by a number of sub-clusters which appear coeval with ages of 3 ± 1 Myr, strongly suggesting formation by the hierarchical fragmentation of a turbulent molecular cloud (Nota *et al.* 2006; Sabbi *et al.* 2007a). NGC 602, on the contrary, appears as a single small cluster of OB stars surrounded by pre-main sequence stars. For both clusters high-resolution spectroscopy of the ionized gas shows little evidence for gas motions. This suggests that at the low SMC metallicity, the winds from the hottest stars are not powerful enough to sweep away the residual gas. Instead we find that stellar radiation is the dominant process shaping the interstellar environment of NGC 346 and NGC 602.

Keywords. stars: formation, stars: luminosity function, mass function, stars: pre-main-sequence, galaxies: individual (SMC), Magellanic Clouds, galaxies: star clusters

1. Introduction

As the closest star forming dwarf galaxy (∼60 kpc), the Small Magellanic Cloud (SMC) represents an ideal laboratory for detailed studies of resolved stellar populations in this extremely common class of objects. Its present day metallicity ($Z = 0.004$) and low dust content (1/30 of the Milky Way) make the SMC the best local analog to the vast majority of late-type dwarfs. Deep images acquired with the Advanced Camera for Survey (ACS) on board of the *Hubble Space Telescope* (*HST*) provide excellent photometry well below the turn-off (TO) of its oldest stellar population, allowing us to infer an accurate star formation history (SFH) over the entire Hubble time.

The high spatial resolution of the Advanced Camera for Surveys (ACS) allows us to spatially resolve even the densest star cluster in the SMC to probe the cluster formation and evolution in late-type dwarf galaxies. Furthermore the availability of multi-wavelength surveys from the radio band to the far-IR, combined with the simple kinematics of the galaxy allow us to identify the possible triggers of star formation (SF).

At solar metallicities, during the first Myr of a star cluster evolution, the powerful winds from the massive stars remove the gas left over from star formation. If star formation efficiency is sufficiently low, the gas dispersion can unbind the cluster (e.g., Bastian & Goodwin 2006). However the reduced stellar wind power at low metallicity can modify early evolution of clusters.

With the aim to understand the impact of global and local conditions on the early star cluster evolution we recently investigated the stellar content of two of the youngest star clusters in the SMC (NGC 346 and NGC 602 respectively) using deep ACS/WFC images in the filters F555W (∼V) and F814W (∼I). We used *Spitzer Space Telescope* (*SST*) IRAC images to investigate if star formation is still ongoing and high resolution spectra to study the kinematics of the ionized gas still associated to these clusters.

2. NGC 346

NGC 346 represents the most active star-forming region in the SMC. It is located towards the northern end of the bar of the SMC and contains almost half of the known O stars of the entire galaxy (Massey *et al.* 1989) which ionized N 66, the largest H II region in the SMC.

HST/ACS images (Plates 1 and 2 in Nota *et al.* 2006) show that even if NGC 346 is ∼3 Myr old (Bouret *et al.* 2003; Nota *et al.* 2006; Sabbi *et al.* 2007a), it still contains some of its residual gas. This suggests that supernova explosions have not occurred yet in the central region of this cluster. This conclusion nicely agrees also with the low diffuse X-ray flux (Nazé *et al.* 2002), and with the neutral gas and CO maps (Rubio *et al.* 2000; Contursi *et al.* 2000).

The photometric analysis of NGC 346 based on *HST*/ACS F555W and F814W deep images (Nota *et al.* 2006; Sabbi *et al.* 2007a) indicates that stars in NGC 346 have an age of 3 ± 1 Myr. The inspection of the $m_{\rm F555W}$ vs. $m_{\rm F555W} - m_{\rm F814W}$ color—magnitude diagram (CMD) reveals the presence of a rich population of faint and red objects (Fig. 1, left panel), consistent with low mass (0.6–3 $M_\odot$) pre-main sequence (preMS) stars, likely coeval with the cluster.

Stars in NGC 346 are not uniformly distributed within the ionized nebula, but are organized in at least 16 sub-clusters that differ in size and stellar densities. 15 of the sub-clusters are still embedded in nebulosities, appear to be connected by filaments of dusts and gas, and are, within the uncertainties of isochrones fitting, likely coeval (Sabbi *et al.* 2007a). The 16th sub-cluster is ∼ 10–15 Myr older, and probably not associated to NGC 346.

From the analysis of *Spitzer* data, Simon *et al.* (2007) found 111 embedded young stellar objects (YSOs) in NGC 346. They found that all but one of the 15 sub-clusters identified in Sabbi *et al.* (2007a) contain YSOs, showing that star formation is still ongoing in the entire region.

The quality of *HST*/ACS data allowed us to derive the present day mass function (PDMF) of NGC 346: the PDMF is Salpeter over the mass range of 0.8–60 $M_\odot$ (Fig. 2, open circles). However the PDMF varies as a function of the radial distance from the cluster center, indicating that the cluster is, probably primordially, mass segregated (Sabbi *et al.* 2007b). Simon *et al.* (2007) noted a similar distribution for the YSOs, with the most massive objects located in the central regions.

Assuming a sound-speed of 10 km s^{-1}, the crossing-time from the cluster center to the periphery is ∼ 2 Myr, which means that NGC 346 is about one crossing-time old.

The observed sub-clustered structure and the coevality of the sub-clusters strongly suggests that NGC 346 was formed by the collapse, and subsequent hierarchical

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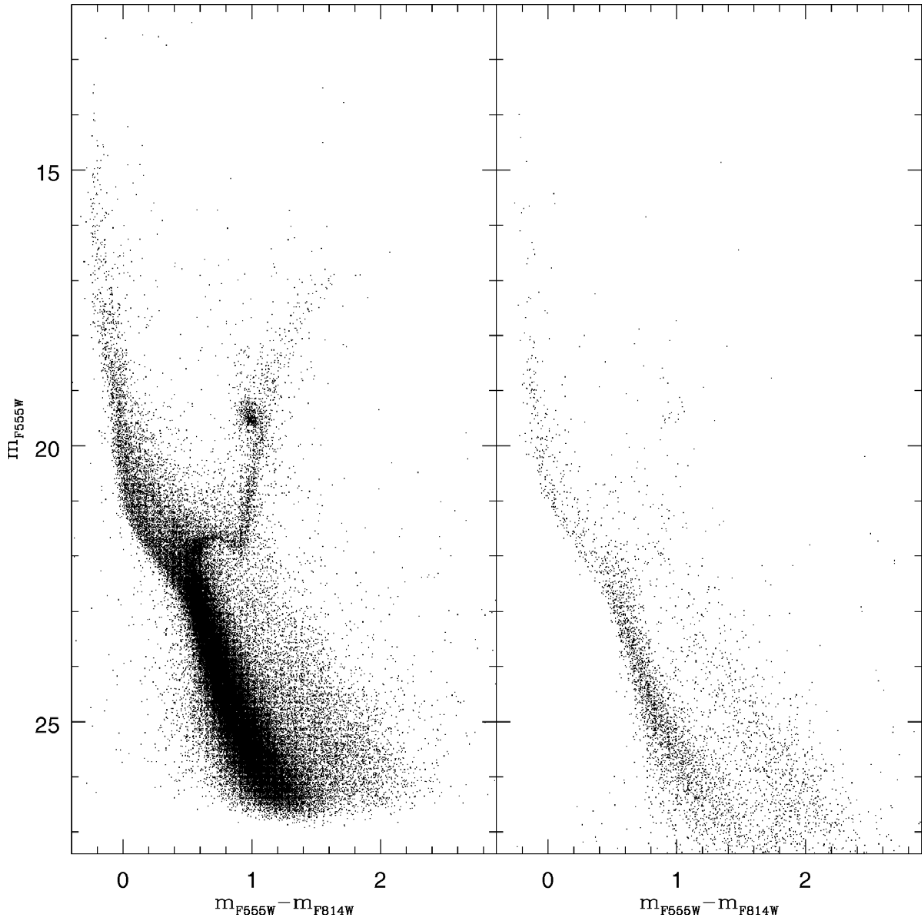

Figure 1. *HST*/ACS $m_{\rm F555W}$ vs. $m_{\rm F555W} - m_{\rm F814W}$ CMDs of NGC 346 (*left panel*) and NGC 602 (*right panel*).

fragmentation of a giant molecular cloud (GMC) into multiple seeds of star formation (Elmegreen 2000; Klessen & Burkert 2000; Bonnell & Bate 2002). In this model, the fragmentation of the GMC is due to supersonic turbulent motions in the gas. The turbulence induces shocks, and causes the formation of filamentary structures, and local density enhancements. High-density regions that become self-gravitating can collapse to form stars, and this occurs simultaneously at different locations within the cloud (Bonnell *et al.* 2003).

The formation of shocks in the gas, due to the initial supersonic turbulence, rapidly removes kinetic energy from the gas (Ostriker *et al.* 2001). To test if this is the case, we obtained high-resolution spectra with the University College London Echelle Spectrograph (UCLES) at the *Anglo-Australian Telescope* (*AAT*). We observed a number of sub-clusters in N 66. Hα and [O III] emission lines show that the ionized gas is quiescent, with no evidence for large-scale gas motions. The Hα profiles are single, with a velocity dispersion of $\sim$14 km s^{-1} and a constant velocity along the length of each slit position (1 arc min). Even at the center of NGC 346, where the most massive stars are located, we detect no significant ionized gas motions, further supporting the idea that NGC 346 is a good observational counterpart of the hierarchical fragmentation models of a GMC.

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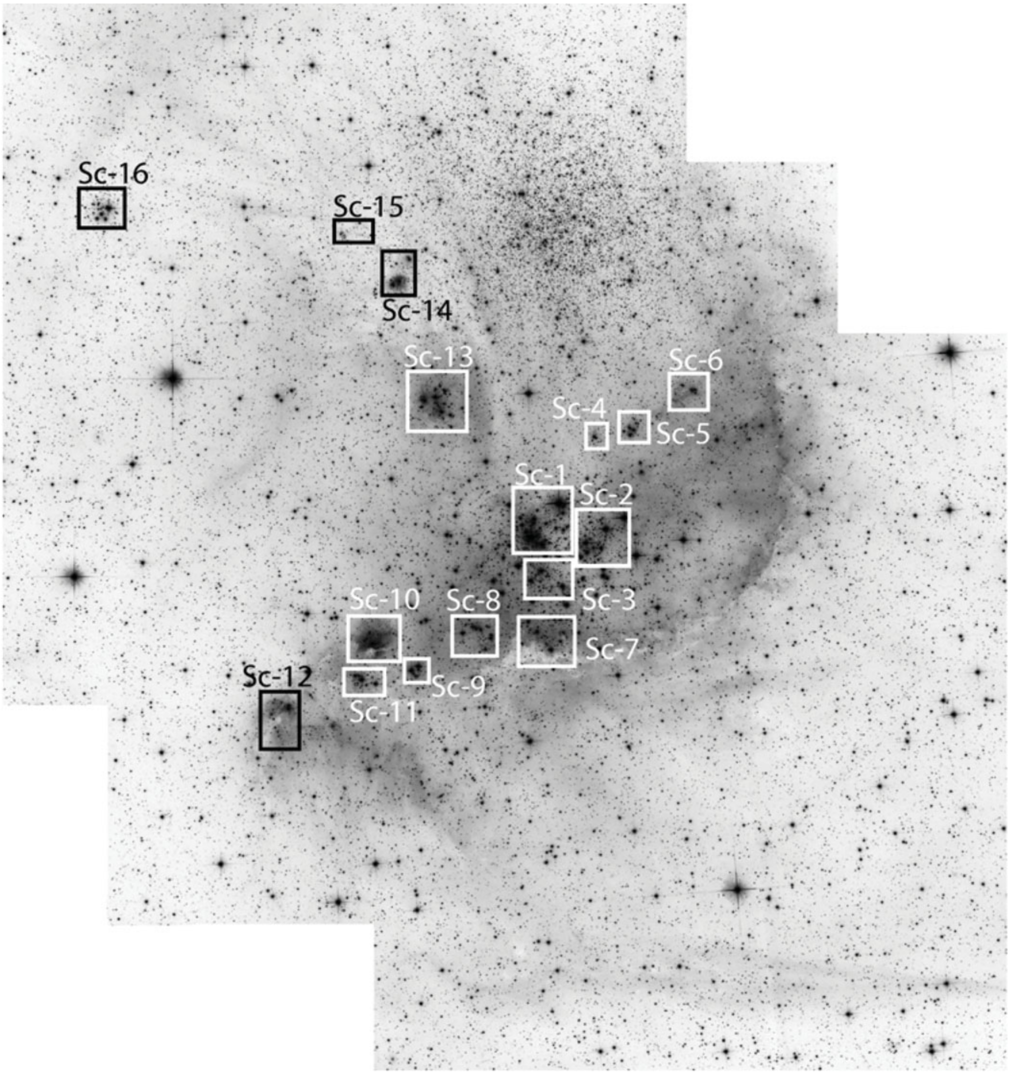

Figure 2. *HST*/ACS F555W image NGC 346 showing the 16 identified sub-clusters.

The lack of large-scale motions also strongly suggests that at the low metallicity of the SMC, stellar winds are much reduced, and the dominant form of interaction is via stellar radiation, rather than by winds, in agreement with Bouret *et al.* (2003) who measured the mass-loss rates of six O stars in the center of NGC 346, and found that their winds are considerably weaker than their Galactic analogs.

3. NGC 602

NGC 602 is a small and bright star forming region, located in the Wing of the SMC. This is the relatively diffuse southeastern region that connects the SMC to the Large Magellanic Cloud via the Magellanic Bridge. NGC 602 is an example of massive star formation in a region with diffuse interstellar medium (ISM) without any apparent direct kinetic trigger, such as a recent nearby supernova.

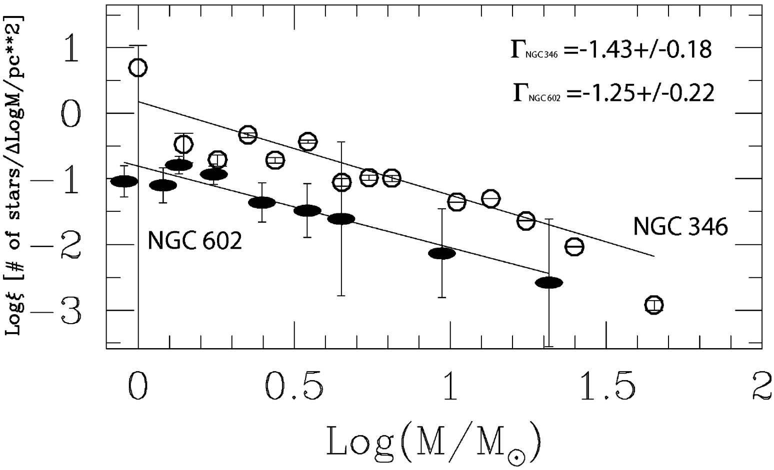

Figure 3. PDMFs of NGC 346 (open circles) between 0.8 and 60 $M_{\odot}$ and NGC 602 (filled ellipses) between 0.8 and 30 $M_{\odot}$.

Its isolation alone makes it a great laboratory for the study of star formation since it lacks the complexities introduced by kinetic interactions and optical confusion with other star clusters. This, combined with the low metallicity and the relatively quiescent environment, also makes it a candidate for comparisons to theoretical works on primordial H II regions driven by Population III stars (e.g., Abel *et al.* 2007).

Two ridges of dust and gaseous filaments surround the central cluster. Many photodissociation regions (PDRs) are visible along the ridges, as well as magnificent "elephant trunks" and "pillars of creation" (see Fig. 1 by Carlson *et al.* 2007). *SST* observations revealed numerous class 0.5 and I YSOs on the verge of the pillars, indicating that SF propagated from the center of NGC 602, and a second generation of stars is currently forming in the periphery of the cluster (Carlson *et al.* 2007).

Figure 1–right panel shows the NGC 602 $m_{\rm F555W}$ vs. $m_{\rm F555W} - m_{\rm F814W}$ CMD. The most striking feature of this CMD is the rich population of pre-MS stars in the mass range 0.6–3 $M_{\odot}$ (Carlson *et al.* 2007). The main-sequence turn-off near $m_{\rm F555W} \simeq 22$ mag, the sub-giant curve also at $m_{\rm F555W} \simeq 22$ mag, and the red clump around $m_{\rm F555W} \simeq 19.5$ mag belong likely to the SMC field stellar population that is present even in this low stellar density region. Isochrone fitting indicates an age of ~ 4 Myr for NGC 602.

We derived the PDMF of NGC 602 in the mass range 0.8–30 $M_{\odot}$ (Fig. 2–filled ellipses). From the weighted least mean squares fit of the data we derived a slope $\Gamma = -1.25 \pm 0.22$ (Cignoni *et al.* 2009) in excellent agreement with what we found in NGC 346.

Even if the morphology of this association is reminiscent of an expanding bubble of gas, UCLES high-resolution spectra show very low velocity dispersion, excluding large-scale motions (Nigra *et al.* 2008). Another possible explanation for the NGC 602 morphology is that we are observing a cavity eroded by the OB UV stellar radiation.

NGC 602 and its associated H II region, N 90, formed in a relatively isolated and diffuse environment. Its isolation from other regions of massive star formation and the relatively simple surrounding H I shell structure encouraged us to try to constrain the processes that may have led to its formation. Using the shell catalog derived from the 21 cm neutral hydrogen (H I) spectrum survey data (Staveley-Smith *et al.* 1997; Stanimirović *et al.* 1999) we identified a distinct H I cloud component that is likely the progenitor cloud of the cluster and the H II region which probably formed in blister fashion from the cloud's periphery. A comparison between H I and H II kinematics suggests that star formation in NGC 602 was triggered by compression and turbulence associated with H I shell interaction ~ 7 Myr ago (Nigra *et al.* 2008).

4. Conclusions

We have recently analyzed the two very young SMC star clusters NGC 346 and NGC 602, which are located in two regions characterized by very different gas and stellar densities. We derived the PDMF of the clusters over two orders of magnitude, further confirming its universality.

Both clusters contain noticeable populations of pre-MS stars and YSOs, indicating that in both cases SF is still ongoing and residual gas is still present. The ionized gas is quiescent, and we did not find evidence of stellar wind interaction, confirming the hypothesis that mechanical feedback is reduced at low metallicities.

Our multi-wavelength approach allowed us to infer very different origins for the clusters, suggesting that different local condition might affect deeply affect the formation and the evolution of star clusters since the earliest phases.

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