4.13 NGC 346: Tracing the Evolution of a Super Star Cluster

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* Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by Aura, Inc., under NASA Contract NAS5-26555

Abstract

We discuss how star formation (SF) has been progressing - in space and time - in NGC 346, the site of the most intense SF in the Small Magellanic Cloud (SMC), as derived from the analysis of optical broadband (\( \sim V \) and \( \sim I \)) and narrow band (\( \sim H\alpha \)) Hubble Space Telescope (HST) images. Our analysis reveals that NGC 346 experienced different regimes of SF, in a number of compact sub-clusters. In the youngest ones, we find a puzzling and intriguing deficiency of massive stars, either suggestive of an evolution of the initial mass function with time, with the youngest sub-clusters not having had sufficient time to build the more massive stars yet, or that high and low-mass stars may form through different mechanisms. The combination of the broad and narrow-band data allowed us to identify bona fide pre-main sequence (PMS) stars that are actively accreting material from their circumstellar disks. Interestingly, the identified PMS stars show a bimodal age distribution - peaked respectively at \( \sim 1 \) and \( \sim 20 \) Myr - with the two generations of stars that appear to be spatially independent.

Introduction

Young super star clusters are rare in the Local Group (LG), and yet they provide important insights on the process of SF in nearby starburst and high-redshift interacting galaxies, formation and disruption of globular clusters, and formation of massive stars.

With more than 30 O-type stars (Massey et al. [1989]; Evand et al. [2006]), the young (~ 3 Myr) cluster NGC 346 is the site of the most intense SF in the SMC, as well as one of the most active regions in the LG. Mid-IR and sub-millimeter observations revealed the presence of several embedded sources in the body of NGC 346, confirming the presence of very recent and/or still ongoing SF (Contursi et al. [2000]; Rubio et al. [2000]).

More recent HST optical observations revealed that the structure of NGC 346 is complex, with its stars being organized in a multitude of almost coeval sub-clusters (Sabbi et al. [2007]; Hennekemper et al. [2008]; Gouliermis et al. [2008]; Fig.4.38 – Left Panel), each of which is hosting massive young stellar objects (YSOs Bollatto et al. [2007]; Simon et al. [2007]; Fig.4.38 – Right Panel).
NGC 346 Star Formation History

We used deep ACS/WFC optical broad-(F555W and F814W) and narrow-band (F658N) HST images to infer how star formation occurred and developed in NGC 346. Photometric studies (i.e. Sabbi et al. [2007], Hennekemper et al. [2008], Gouliermis et al. [2008]) of this dataset indicate that SF has taken place in a variety of sub-clusters at different local conditions.

To better constrain the star formation history (SFH) and the evolution of this complex region we used a standard application of the synthetic colour-magnitude diagram (CMD) method (see, e.g., Tosi, et al. [1991], Cignoni et al. [2006], Cignoni & Tosi [2010]) and a novel technique based on the identification of bona fide pre-main-sequence (PMS) stars with active accretion (De Marchi, Panagia & Romaniello [2010]).

History and modes of star formation from synthetic CMDs

To trace how SF occurred and evolved in NGC 346 itself we used objects on the upper main-sequence (UMS) and objects still on the PMS. We considered as UMS stars all objects above the Turn-On (TON) of a 3 Myr isochrone and bluer than $V - I = 0.2$ (black open diamonds in Fig. 4.39 – Top Left Panel). In doing this we sampled the intermediate and high-mass stars. To trace the distribution of PMS stars we considered objects redder than the 3 Myr isochrone with magnitude in the range $22.5 < V < 25$.  

Figure 4.40: **Left Panel:** Position of the three groups of sub-clusters in NGC 346. **Right Panel:** SFH of the SMC field around NGC 346. For sake of clarity the most recent 500 Myr are zoomed in the upper right onset. The uncertainty on the SFR is also shown for each age bin. The two episodes of SF associated to BS90 and NGC 346 are not included.

(Blue open circles) and fainter than \( V = 25 \) (magenta open squares, hereafter LPMS). According to this selection, PMS stars trace a population younger than \( \sim 3 \) Myr, the UMS sample include MS stars as old as 600 Myr. Moreover, while there is no doubt that the PMS and LPMS samples are free from any contamination, the UMS sample can include a minor fraction of PMS stars starting to approach the MS.

The top right, bottom right, and bottom left panels of Fig. 4.39 show the location of the selected stellar populations. These distributions provide a clue to the evolution of NGC 346. In particular we find that half of the UMS stars are clumped into the most massive sub-clusters SC-1, SC-13, and SC-16, while the remaining half are more evenly distributed and are probably foreground and background stars. PMS and LPMS stars are found almost exclusively either clumped or irregularly arranged along filaments.

A further intriguing aspect of the star spatial distribution is that not all the sub-clusters visible in the UMS map are detected in the PMS maps and vice versa.

We divided the sub-clusters in three groups, based on the fraction of PMS stars with the respect of UMS (Fig. 4.40 - Left Panel). The bulk of the stars in Group \( i \) sub-clusters are well consistent with a major star-forming episode started about 6 Myr ago and lasted about 3 Myr. After that, their star formation activity has proceeded at a lower rate (Cignoni et al. [2011]). As already noted by Hennekemper et al. [2008], models do not fully reproduce the large colour spread shown by PMS stars. Since our PMS evolutionary tracks do not include circumstellar reddening, a more likely explanation is that the redward broadening of the PMS stars is caused by variable reddening affecting individual PMS stars. Moreover, our models seem to underestimate the observed PMS counts by about 40%. We speculate that a very young generation of stars, so young not to have had time to assemble more massive stars, could account both for the observed excess of PMS stars and for the intrinsic redness of such stars (Cignoni et al. [2011]).

As we already pointed out in Sabbi et al. [2008], in NGC 346 massive stars are underrepresented. In particular we find that Group \( II \) sub-clusters are dominated by low-mass PMS stars, with the PMS/UMS ratio being at least three times higher than in Group \( i \). Such a population should have a MS counterpart, which is not visible, however. Furthermore, the PMS stars are redder than in Group \( i \). We speculate that in Group \( II \) SF is occurring only now, and that PMS stars are redder because they still retain some/more circumstellar material. The lack of massive stars in this regions can be ascribed, as suggested by Panagia et al. [2000], either to the fact that for different stellar masses SF requires different initial conditions, or that more massive stars may form later than low-mass stars (e.g. because they need more time to collect enough material to form). In this case the Group \( II \) sub-clusters are simply too young to have produced massive stars (Cignoni et al. [2011]). Finally, Group \( III \) sub-clusters have characteristics intermediate between Group \( i \) and \( II \).

From the comparison of the observed \( V \) versus \( V - I \) CMD to the synthetic ones and the analysis of the spatial distribution of the stellar component in the NGC 346 region we concluded that in the field of the SMC 60% of the mass astration occurred earlier than 5 Gyr ago (Fig. 4.40 - Right Panel), with a peak between 5 and 7 Gyr ago (Cignoni et al. [2011]), in agreement with the SFH of other regions of the SMC derived by other authors (e.g. Dolphin et al. 2001; McCumber et al. 2005; Cignoni et al. 2009; Noël et al. 2009; Sabbi et al. 2009).

The average star formation rate density in the field surrounding NGC 346 is \( 1.5 \times 10^{-9} \) M\(_\odot\) yr\(^{-1}\) pc\(^{-2}\). This value is in agreement with those derived by Noël et al. [2009] for several SMC regions. However, the rate of star formation in the NGC 346 region appears to have increased in the last tens
Figure 4.41: **Left Panel**: Colour-colour diagram of the 18,764 stars with error $\sigma_3 \leq 0.1$ mag. The dashed line represents the running median $V - H\alpha$ colour, obtained with a box-car size of 100 points, whereas the thin solid line shows the model atmospheres of Bessell et al. [1998]. The arrow in the figure corresponds to the reddening vector for $A_V = 2.7$ or $E(V - I) = 1$. The red dots mark the 791 objects with a $V - H\alpha$ excess larger than 4$\sigma$. **Right Panel**: $H\alpha$ equivalent width of the stars in the field of NGC 346, as a function of their $V - I$ colour. Red circles indicate the 694 sources with $W_{eq}(H\alpha) < -20$ Å (or $< -50$ Å for stars hotter than 10,000K).

As customary, we use negative equivalent widths for emission lines.

of Myr from a relatively lower and steady regime. In the last 100 Myr the average star formation rate density in the field is about $1.4 \times 10^{-8} \, M_\odot \, yr^{-1} \, pc^{-2}$, two orders of magnitude higher than in nearby late-type dwarfs, and similar to the quietest cases of Blue Compact Dwarfs (see Tolstoy et al. [2009] and references therein).

**NGC 346 SFH as derived from bona fide PMS with active accretion**

We used the self-consistent method recently developed by De Marchi, Panagia & Romaniello [2010] that combine broad-band V and I photometry and narrow-band $H\alpha$ imaging to identify all stars with excess $H\alpha$ emission in the region around NGC 346. This technique allows us to derive for all of these stars the accretion luminosity $L_{acc}$ and mass accretion rate $\dot{M}_{acc}$.

Following the method developed in De Marchi, Panagia & Romaniello [2010], we identified 791 PMS candidates with $H\alpha$ excess above the 4$\sigma$ level with respect to the reference provided by normal stars (Fig. 4.41 – Left Panel). Their average $H\alpha$ luminosity is $2.7 \times 10^{31}$ erg s$^{-1}$ or $\sim 10^{-2} \, L_\odot$. We have also determined the equivalent width of the $H\alpha$ emission line of these objects (Fig. 4.41 – Right Panel) and have classified as bona fide PMS stars all those with $W_{eq} < -20$ Å (or $< -50$ Å for stars with $T_{eff} > 10,000$K). These conditions guarantee that our sample is free from contamination due to the chromospheric activity of older objects or to the rotational winds of Be stars. A total of 694 objects satisfy these conditions.

By comparing the locations of these objects in the H-R diagram with the PMS evolutionary models of the Pisa group for metallicity $Z = 0.002$ (Fig. 4.42 – Left Panel), we derived masses and ages for 680 bona fide PMS stars. Masses range from 0.4 $M_\odot$ to 4 $M_\odot$, with an average value of $\sim 1 \, M_\odot$. The ages show a clear bimodal distribution with two peaks at $\sim 1$ Myr and $\sim 20$ Myr and very few objects around $\sim 8$ Myr, revealing the presence of two distinct but equally populous generations of stars (De Marchi et al. [2011a]).

The size of our PMS sample, and its spread in age and mass, allowed us to study the evolution of the mass accretion rate as a function of stellar parameters. Regardless of the mass of the star, we find that the mass accretion rate decreases with roughly the square root of age, which is $\sim 3$ times slower than what is currently predicted by models of viscous disc evolution, and that the more massive stars have a systematically higher mass accretion rate in proportion to their mass. Our analysis indicates that, at least in low metallicity environments, a considerable amount of mass is accreted during the PMS phase, and that the PMS evolution of moderate-mass stars ($< 2 \, M_\odot$) should be reconsidered and recalculated taking into account the high $M_{acc}$ values, since for a given MS mass the evolutionary time needed to reach the ZAMS will be longer than what is currently estimated by models that assume $M_{acc} = 0$ after the first few $10^4$ yr (De Marchi et al. [2011a]).

We used age and other physical parameters of the PMS stars with active $H\alpha$ accretion to study
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Figure 4.42: Left Panel: Hertzsprung-Russel diagram of the PMS candidate stars with active accretion, as derived from their H$\alpha$ excess. Thick solid lines show the evolutionary tracks from the Pisa group (Degl’Innocenti et al. [2008]; Tognelli et al. [2011]) for metallicity $Z = 0.002$ and masses from $0.5 \, M_{\odot}$ to $4 \, M_{\odot}$, as indicated. The corresponding isochrones are shown as thin dashed lines, for ages of 0.125, 0.25, 0.5, 1, 2, 4, 8, 16 and 32 Myr from right to left. Right Panel: Spatial density distribution of young ($< 7$ Myr; red lines) and old ($> 7$ Myr; yellow lines) PMS stars in NGC 346, overlaid on a negative HST/ACS H$\alpha$ image of the region. The (0,0) position in this figure corresponds to $RA = 0^h59^m8^s$, $DEC = -72^\circ10'32''$ (J2000), while North is up and East to the left. Blue circles mark the position of young ($< 7$ Myr) massive stars brighter than $-2 \times 10^4 L_{\odot}$.

how SF proceeded in the region of NGC 346 in the last $\sim 30$ Myr (De Marchi et al. [2011b]). Except for the regions near the centre of NGC 346, the stars belonging to the two generations have very different spatial distributions: $\sim 1/3$ of the older generation occupies an arc-like gas structure to the south and west of NGC 346 that had previously been interpreted as the ionization front caused by the OB stars at its centre. Although the morphology of the arc could have suggested a case of triggered star formation, this is clearly not a viable option since the central massive stars are at least 10 – 20 Myr younger than the objects on the arc and cannot have triggered their formation (Fig. 4.42 – Right Panel). The compact distribution of older PMS stars along the arc-like structure suggests that they have formed there from the gas that is still visible and have not (yet) been affected by the massive OB stars at the centre of NGC 346. This picture is consistent with the very low velocity dispersion ($< 3$ kms$^{-1}$) of the ionized gas.

Finally we once again note that, with the exception of the most central regions, there is no correspondence between the positions of young PMS stars and massive O-type stars of similar age, suggesting that the conditions (and possibly also the mechanisms) for their formation must be rather different (Panagia et al. [2000]; De Marchi et al. [2011b]).

Summary & Conclusions

We used both a standard synthetic CMD method and a novel technique to identify bona fide PMS stars with active accretion to investigate how SF has been progressing - in space and time - in NGC 346, the site of most intense SF in the SMC. Both methods indicate that NGC 346 experienced different regimes of SF over several tens of Myr.

The youngest regions show an intriguing deficiency of massive stars, either suggestive of an evolution of the initial mass function with time, with the youngest sub-clusters not having had sufficient time to build the more massive stars yet, or that high and low-mass stars may form through different mechanisms.

Bibliography

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