DISCOVERY OF A POPULATION OF PRE–MAIN-SEQUENCE STARS IN NGC 346 FROM DEEP HUBBLE SPACE TELESCOPE ACS IMAGES

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ABSTRACT

We report the discovery of a rich population of low-mass stars in the young, massive NGC 346 star-forming region in the Small Magellanic Cloud from deep V, I, and Hα images taken with the Hubble Space Telescope Advanced Camera for Surveys. These stars have likely formed together with the NGC 346 cluster, ∼3–5 Myr ago. Their magnitudes and colors are those of pre–main-sequence stars in the mass range 0.6–3 M☉, mostly concentrated in the main cluster, but with secondary subclusters spread over a region across ∼45 pc. These subclusters appear to be spatially coincident with previously known knots of molecular gas identified in ground-based and Infrared Space Observatory observations. We show that NGC 346 is a complex region, being shaped by its massive stars, and the observations presented here represent a key step toward the understanding of how star formation occurred and has progressed in this low-metallicity environment.

Subject headings: galaxies: star clusters — Magellanic Clouds — open clusters and associations: individual (NGC 346) — stars: evolution — stars: pre–main-sequence

1. INTRODUCTION

N66 is the most massive and active star-forming region in the Small Magellanic Cloud (SMC), and the star cluster NGC 346 is its ionizing core. It contains more than half of the known O stars in this galaxy, as well as associated CO clouds (Rubio et al. 2000). The upper end of its stellar mass distribution has been well studied in recent years; very early O-type stars (O3) and high-mass (45–100 M☉) stars were found, suggesting a slope of the initial mass function (IMF) in NGC 346 very similar to the slope for massive stars in the LMC and solar neighborhood [Γ = d(log ξ)d(log M) = −1.9] and an age of ∼3 Myr (see Bouret et al. 2003 and references therein). Massey et al. (1989) also suggested the presence of sequential star formation in NGC 346, with star formation beginning at the southwest side of the association and spreading toward the central cluster.

While a wealth of information is available on the upper end of the stellar mass distribution in NGC 346, little is known of the low end of the distribution. The SMC is characterized by a dust-to-gas mass ratio that is 30 times lower than in the Galaxy (Stanimirović et al. 2000) and a metallicity about one-fifth that of the Galaxy. Might these differences have had an impact on the cluster formation mechanism and their distribution of stellar masses? To answer this question we have begun a comprehensive investigation of star formation in the SMC, from the ground and with the Hubble Space Telescope (HST). This Letter presents the first results on NGC 346.

2. OBSERVATIONS

We used the HST Advanced Camera for Surveys (ACS) Wide Field Channel (WF) to map NGC 346 in the filters F555W (∼V), F814W (∼I), and F658N (∼Hα). The observations were carried out between 2004 July 13 and 17, as part of Cycle 13 proposal 10248 (PI A. Nota). In the broadband filters, nine deep images (each 200 s in size) were obtained in each filter, partially overlapping to yield optimal spatial coverage of the NGC 346 region. An additional set of short exposures was taken in the same instrumental configuration to perform accurate photometry of the brightest stars. A single image of NGC 346 was taken in the light of Hα, with an exposure time of 1542 s.

In Figure 1 (Plate 1), we show the fully reduced, multidrizzled and combined V1 color composite image of NGC 346. The image covers an area of ∼5′ × 5′, which corresponds to ∼87 × 87 pc for a distance to the SMC of 59.7 kpc (Dolphin et al. 2001). The exposure time in the central region is ∼4100 s in each filter. In Figure 2 (Plate 2) we show the fully reduced Hα image. All images were reduced using the standard STScI ACS pipeline CALACS (Pavlovsky et al. 2004), to remove the instrumental signatures: bias, dark current, and flat-field response. Cosmic rays were removed. The dithered images were combined using the MultiDrizzle package, which also corrected the images for geometric distortion and increased the point-spread function (PSF) sampling. The final pixel scale was 80% of the original ACS pixel.

Photometry was performed on the drizzled images by aperture and PSF fitting, using the DAOPHOT package within IRAF. Stars were automatically detected with the routine DAOFIND in all the frames, with the detection threshold set at 4 σ above the local background level. Features misinterpreted...
as stars, such as noise spikes, were rejected. A spatially variable PSF was computed for both the V and I images, using \( \sim 140 \) isolated stars in different positions on the images. No correction for charge transfer efficiency (CTE) was applied. However, preliminary CTE determinations indicate that this correction is small and can therefore be neglected in this first analysis without changing the overall conclusions. Our final photometry is calibrated on the ACS Vega-mag system, with zero points adopted from Sirianni et al. (2005) of 25.724 and 25.501 for the V and I filters, respectively.

3. MORPHOLOGY OF THE NGC 346 REGION

The deep HST ACS images show an unprecedented level of detail in the NGC 346–N66 complex. The NGC 346 cluster at the center is resolved into at least three subclusters, and a myriad of small compact clusters are visible throughout the region. Some of these clusters appear to be still embedded in dust and nebulosity, and they might be sites of recent or ongoing star formation. The diffuse nebulosity is due to the presence of H\(\alpha\) and [O \(\text{iii}\)] \(\lambda\lambda 4959, 5007\) in the V filter, which indicate the bright underlying H\(\alpha\) region. This extends to the north with arches and ragged filaments but is delineated to the south-southwest by a sharp fanlike “ridge,” which encompasses the entire cluster. This ridge is especially evident in the H\(\alpha\) image of the region (Fig. 2). Extensive dust lanes are clearly visible along this ridge. Dust patches are also visible throughout the region, most likely the remnants of the original molecular cloud (Mizuno et al. 2001). A previously known globular-looking concentration of older stars (Bica & Schmitt 1995) is visible to the north of the NGC 346 cluster. The stellar content of this feature is consistent with being SMC field population, with an age of \( \sim 4.5 \) Gyr.

4. COLOR-MAGNITUDE DIAGRAM

The V and I photometric data with photometric errors smaller than 0.1 mag were used to construct the \((V, V-I)\) color-magnitude diagram (CMD) of the entire NGC 346 region. The CMD (Fig. 3, black dots) contains \( \sim 80,000 \) stars. Thanks to the high photometric accuracy obtained with ACS, these stars produce a very clean CMD, with a well-defined, narrow main sequence (MS) down to \( V \approx 26 \). The photometric errors in magnitude and color are indicated directly in the CMD by the bars at left. A pronounced old MS turnover is clearly visible, at \( V \approx 22 \), and so is the red clump, at \( V \approx 19.5 \). The CMD morphology also reveals a young population, indicated by the bright, blue MS, extending from the MS of the old SMC stellar population. Below \( V \approx 21 \), a group of very red faint stars is detected to the right of the MS. It is plausible that this split MS could be due to differential reddening. However, the absence of such a split in the upper part of the MS leads us to believe that these are stars that are less massive than \( \sim 3 M_\odot \) (down to 0.6 \( M_\odot \)) that formed with the rest of the central cluster but have not reached the MS yet (pre-MS stars).

Analyzing separately the stellar content of the individual clusters we can resolve in the ACS images, we can better characterize the local stellar population. The orange circles in Figure 3 highlight the observational CMD for the core of NGC 346. They indicate stars within a radius of \( \sim 8'' \) from the cluster center.

We superposed onto these CMDs isochrones for pre-MS stars (from Siess et al. 2000) and for MS and post-MS stars (from Lejeune & Schaerer 2001 and Pietrinferni et al. 2004), to define the age and the nature of the population observed in the central cluster. We find the presence of at least two different populations:

1. A composite SMC field population covering a wide range in age but dominated by the 4.5 Gyr component.
2. A very young population of age \( \approx 3-5 \) Myr. Stars less massive than \( \approx 3 M_\odot \) (down to 0.6 \( M_\odot \)) are still in the pre-MS phase, approaching the MS.

An intermediate-age population \( \approx 150 \) Myr might also be present.

5. THE CANDIDATE PRE-MS STARS

The pre-MS stars are, as expected, faint \((V < 21)\) and red \((1.5 < V-I < 2.2)\). The CMD isochrone fit indicates that they likely formed with the rest of the cluster \((\approx 3-5 \) Myr ago\) but have not reached the MS yet. They are in the mass range 0.6–3 \( M_\odot \). Their spatial distribution is shown in Figure 4. They appear concentrated at the center of NGC 346, mostly in the central subclusters, but also in the small compact clusters that are located in the direction perpendicular to the NGC 346 main body, extending to the northeast. Their spatial location appears coincident with the clumps of neutral material identified by Rubio et al. (2000). This is particularly evident from Figure 4, where we have superposed an indication of the Infrared Space Observatory (ISO) LW2 emission peaks (7 \( \mu \text{m} \))—from Figure 8 of Rubio et al. (2000)—onto the spatial distribution of the pre-MS stars. The spatial density of the pre-MS stars appears to decrease as we move from the center toward the south-southwestern ridge, where we observe the dust lanes. As also suggested by Rubio et al. (2000), it is likely that the region, and especially the ridge, may be a site of more recent or ongoing star formation and that the forming stars are still embedded in dust and too faint to be visually detected in the ACS images.
6. STAR FORMATION IN NGC 346

The region around NGC 346 is remarkable, having displayed a high level of activity in the recent past. To the northeast of NGC 346 there is a known supernova (SN) remnant, SNR 0057–7226, first identified as a bright source in Einstein X-ray observations (Inoue et al. 1983). Subsequently, Chu & Kennicutt (1988) and Ye et al. (1991) confirmed the remnant and indicated a size of 3′.2. The remnant is approximately centered on, but unlikely to be associated with, the remarkable luminous blue variable HD 5980. From the expansion velocity derived from Far Ultraviolet Spectroscopic Explorer observations of ≃150 km s⁻¹ (Danforth et al. 2003), we can derive a dynamical timescale of $2 \times 10^5$ yr and set a lower limit to the epoch of the SN explosion. It is clear that SNR 0057–7226 has been interacting with the surrounding region, and the O vi, C iii, and X-ray emission observed (Danforth et al. 2003) arises from the shock interaction. A second SN remnant has been identified by Ye et al. (1991) to the southwest of NGC 346. This is SNR 0056–7233. Not much is known about this SN, except that it is located at a distance of ~5.4 pc from the center of NGC 346. Two concentric bubbles are seen to the northeast in the Hα region shown in Figure 2; we believe they are most likely shaped by the powerful winds of HD 5980.

Observations by Rubio et al. (2000) and Contursi et al. (2000) have painted a detailed picture of the molecular gas and dust component in N66 and NGG 346. Their observations indicate that the molecular gas has been mostly dissociated by the UV radiation of the hottest stars; what has not been dissociated is detected in small, compact clumps, which appear to be spatially coincident with the regions where we observe the pre-MS stars (Rubio et al. 2000). Specifically, their CO (2–1) observations with the Swedish-ESO Submillimetre Telescope indicate clumps of emission in the NGC 346 central cluster, and even stronger emission along the direction perpendicular to the NGC 346 main body, to the northeast. These clumps are exactly where we find the highest concentration of pre-MS stars. There appears not to be much molecular gas or dust outside the NGC 346 main body, casting doubt on the notion that the southwest ridge might not be at the boundary with a molecular cloud as initially suspected (Rubio et al. 2000).

We have shown that N66–NGC 346 is a complex region that has been shaped by the evolution of the most massive stars, some of which have already exploded as supernovae and are compressing the central region from different directions. The outstanding question will be to understand how star formation has been triggered and has been progressing in this region. Further necessary work on this region includes spectroscopic characterization of the pre-MS stars and spectroscopic observations of the gas kinematics. On the theoretical side, NGC 346 can easily become an ideal laboratory to test current theories of star formation at low masses.

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Fig. 1.—VI color composite of three partially overlapping ACS WF images of NGC 346, covering a total area of $5' \times 5'$. North is up, and east is to the left. The yellow circle (radius $8''$) marks the position of NGC 346.
PLATE 2

Fig. 2.—Ha ACS WF image of the central NGC 346 region, covering an area of 200" × 200". North is up, and east is to the left.