

NGC 346 IN THE SMALL MAGELLANIC CLOUD. IV. TRIGGERED STAR FORMATION IN THE H II REGION N 66

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ABSTRACT

Stellar feedback, expanding H II regions, wind-blown bubbles, and supernovae are thought to be important triggering mechanisms of star formation. Stellar associations, being hosts of significant numbers of early-type stars, are the loci where these mechanisms act. In this part of our photometric study of the star-forming region NGC 346/N 66 in the Small Magellanic Cloud, we present evidence based on previous and recent detailed studies, that it hosts at least two different events of triggered star formation and we reveal the complexity of its recent star formation history. In our earlier studies of this region (Papers I, III) we find that besides the central part of N 66, where the bright OB stellar content of the association NGC 346 is concentrated, an arc-like nebular feature, north of the association, hosts recent star formation. This feature is characterized by a high concentration of emission-line stars and Young Stellar Objects, as well as embedded sources seen as IR-emission peaks that coincide with young compact clusters of low-mass pre-main sequence stars. All these objects indicate that the northern arc of N 66 encompasses the most current star formation event in the region. We present evidence that this star formation is the product of a different mechanism than that in the general area of the association, and that it is triggered by a wind-driven expanding H II region (or bubble) blown by a massive supernova progenitor, and possibly other bright stars, a few Myr ago. We propose a scenario according to which this mechanism triggered star formation away from the bar of N 66, while in the bar of N 66 star formation is introduced by the photo-ionizing OB stars of the association itself.

Subject headings: Magellanic Clouds — stars: winds, outflows — ISM: bubbles — HII regions — supernova remnants — clusters: individual (NGC 346)

1. INTRODUCTION

Massive OB stars, not having an optically visible pre-main sequence (PMS) contraction phase, appear almost immediately after their birth on the main sequence (e.g. Stahler & Palla 2005). They are mostly grouped in stellar associations, loose concentrations of stars, which host also significant numbers of intermediate- and low-mass PMS stars (see review by Briceño et al. 2007). When the far-UV radiation of the bright OB stars reaches the surface of the parental molecular cloud, a photo-dissociated region (PDR) develops. Nebula LHA 115-N 66 or in short N 66 (Henize 1956), the brightest H II region in the Small Magellanic Cloud (SMC), being very rich in early-type stars, is certainly an excellent example of an extragalactic PDR. The stellar association NGC 346, located in the central part of the nebula, hosts the largest sample of spectroscopically confirmed OB stars in the SMC (Massey et al. 1989), which have been the subject of several previous investigations (Niemela et al. 1986; Walborn et al. 2000; Evans et al. 2006).

These massive stars evolve rapidly, and immediately start to ionize the cloud, blowing its material away. The degree of ionization decreases outwards, and a thin barrier develops that segregates the ionized from the atomic gas. Molecular hydrogen is not fully ionized behind this front, but partly dissociated, while CO molecules which are located a bit deeper into the cloud are more easily dissociated than H₂ by absorbing UV photons. A correlation between H₂ infrared emission

and CO lines, characteristic of a PDR, has been found for the region of NGC 346/N 66 by Contursi et al. (2000) and Rubio et al. (2000). These authors define the “bar” of N 66 as the oblique bright emission region, extending from southeast to northwest centered on NGC 346. They suggest that *star formation has taken place as a sequential process in the bar of N 66*, resulting in several embedded sources, seen as IR-emission peaks in the 2.14 μm H₂ line and the ISOCAM LW2 band (5 - 8 μm). These peaks are alphabetically numbered from “A” to “I” (Contursi et al. 2000), with the association NGC 346 itself coinciding with peak “C”.

Recent studies reconstruct the star formation history in nearby Galactic OB associations, and provide observational evidence for sequential and triggered star formation in their vicinity. Preibisch & Zinnecker (2007) conclude from their study of the Scorpius-Centaurus OB association that the formation of whole OB subgroups (each consisting of several thousand stars) requires large-scale triggering mechanisms such as shocks from expanding wind and supernova driven super-bubbles surrounding older subgroups³. Since the low-mass stellar members of associations remain in their PMS phase for $\lesssim 30$ Myr, they play a key rôle in the understanding of star formation in the vicinity of these systems (Briceño et al. 2007). Consequently, the recent discovery of a plethora of low-mass PMS stars in the region of NGC 346/N 66 with photometry from the *Advanced Camera for Surveys* (ACS) onboard HST (Nota et al. 2006; Gouliermis et al. 2006, hereafter Paper I) can contribute significantly to the clarification of the mechanisms that may act in this extraordinary star-forming region.

³ According to these authors, other triggering mechanisms, like radiatively driven implosion of globules, also operate, but seem to be secondary processes, forming only small stellar groups rather than whole OB subgroups with thousands of stars.

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The subsequent investigation of these PMS stars in NGC 346/N 66 (Sabbi et al. 2007, hereafter SSN07; Hennekemper et al. 2008, hereafter Paper III) demonstrated that indeed they are clustered in several compact concentrations, some of them coinciding with the IR-emission peaks of Contursi et al. (2000; detected also with *Spitzer*, see §2.1), verifying the existence of stellar subgroups in the region, similarly to galactic associations. Not being able to resolve differences in age smaller than 1 - 2 Myr in the individual CMDs of these sub-clusters, SSN07 suggest that “all sub-clusters appear coeval with each other”. According to these authors, this coevality is a signature of the star formation conditions predicted by the hierarchical fragmentation of a turbulent molecular cloud model (Klessen & Burkert 2000; Bonnell & Bate 2002; Bonnell et al. 2003).

However, our analysis on the clustering properties of the PMS stars in NGC 346/N 66 (Paper III) showed that *there are significant age differences between some sub-clusters and the association itself*. Specifically, three compact PMS clusters located to the north of the bar of N 66 are found to be not older than 2.5 Myr, while the CMD of the main body of the association NGC 346 show indications of an underlying older PMS population. This clearly suggests that these northern clusters are probably formed *after* the central stellar association. As we discuss later, triggering mechanisms for star formation such as those described by models of ionization shock fronts from OB stars (e.g. Kessel-Deynet & Burkert 2003) or wind-driven shock waves (e.g. Vanhala & Cameron 1998) may explain better their formation. Indeed, while a sequential star formation mechanism has been suggested to take place in the bar of N 66, around the association (Rubio et al. 2000), the existence of young compact PMS clusters *away* from it to the north of the association, does not quite fit in the hypothesis that this mechanism propagated from the center of N 66 along the bar. The triggering agent of these clusters may well be located outside of the bar.

In this paper we consider the findings from earlier and recent comprehensive investigations of the region NGC 346/N 66 to attempt a clearer understanding of the mechanisms that shape the recent star formation of this outstanding extragalactic star-forming region. Our aim is to provide answers to two important questions: i) *Is the star formation away from the association NGC 346 the product of triggered fragmentation of the cloud alone?* ii) *Is the photo-dissociation by the early-type stars of NGC 346 in the center of N 66 the only triggering mechanism in the region?* In section 2 we present evidence that this region has a far more complicated recent star formation history than what was previously considered, and that the most recent star formation event could not have been triggered by the central association. In section 3 we propose a scenario for the recent star formation in the northern part of the region NGC 346/N 66 and we indicate a nearby massive supernova progenitor, located at the northeast of the bar of N 66, as the triggering agent. We also discuss the possibility that other nearby massive stars away from the association may have also contributed to this mechanism. We present supporting evidence to this scenario using analyses of massive stellar content and gas kinematics of this region. Concluding remarks are given in section 4.

2. STAR FORMATION IN THE REGION OF NGC 346/N 66

2.1. Star Formation away from the bar of N 66

Recent *Spitzer* IR observations of NGC 346/N 66 revealed a rich sample of embedded sources, identified as candidate

Young Stellar Objects (YSOs; Bolatto et al. 2007; Simon et al. 2007). A large concentration of these sources are located in the bar of N 66, in agreement with the distribution of the PMS stars found with our ACS photometry (Paper III), and they coincide with the emission peaks of this area identified by Rubio et al. (2000; peaks A, B, C, D, E, H and I; see also their Fig. 8). However, another important concentration of YSOs is located to the north of the bar, coinciding with two additional emission peaks (peaks F and G) and with a second concentration of PMS stars, which forms an arc-like feature, extending from southwest to northeast. The ACS image of the region in $H\alpha$ (Paper III), the $8\mu\text{m}$ *Spitzer* image (Simon et al. 2007), as well as the maps of the CO(2-1) line emission (Rubio et al. 2000) give further support for the existence of this feature⁴. Three compact clusters of PMS stars are identified by us (Paper III) and SSN07 in this arc-like feature (clusters 2a, 2b, and 3 in Paper III, and Sc-13, 14 and 15 in SSN07) to coincide with both IR-emission peaks. The PMS stars in these clusters are found to be younger than those of the bar, implying that they are more recently formed. Moreover, this northern feature is also characterized by a high concentration of emission-line stars found with our ACS photometry in $H\alpha$ (Paper III). These facts clearly suggest that indeed star formation currently takes place in an extended feature away from the bar of N 66, northeast of NGC 346.

This feature can be easily distinguished in the color-composite image shown in the left panel of Fig. 1. We constructed this image from observations of the general area around NGC 346/N 66 with XMM-Newton in X-rays (blue), ESO NTT in [O III] (green) and *Spitzer*/IRAC in the $8\mu\text{m}$ band (red). The XMM-Newton observations have ID 0110000201 (PI: J. Bleeker), and they have been used in variability studies of X-ray sources (Nazé et al. 2004) and in the investigation of high mass X-ray binaries (Sasaki, Pietsch & Haberl 2003; Shtykovski & Gilfanov 2005) in the region of NGC 346/N 66. The [O III] (501.1 nm) image of NGC 346/N 66 was taken with NTT/EMMI within the ESO Program 56.C-0379 (PI: I. J. Danziger) and it was also presented in the analysis by Rubio et al. (2000). The $8\mu\text{m}$ imaging data have been obtained with the Infrared Array Camera (IRAC; Fazio et al. 2004) onboard the *Spitzer Space Telescope* within the GTO Science Program 63 (PI: J. R. Houck) on 2004 April 20, and it has been used for the detection of candidate YSOs in the region (Simon et al. 2007).

The association NGC 346 is located within the bar of N 66, almost at the center of the image of Fig. 1 (left panel). From this image, as well as from the ones taken with *HST*/ACS (see Nota et al. 2006) and *Spitzer*/IRAC (see Simon et al. 2007) it can be seen that there is a relation between NGC 346 and a southern dusty arc feature. This one seems to outline the ionization front of the remaining cloud, due to the powerful winds of the OB stars of the association. However, the shape and orientation of the star-forming feature away and to the north of NGC 346, located at the top left part of the image, suggests that it is triggered probably by the same kind of mechanism, but this process *could not be produced* by the photo-dissociation of the cloud by the ionizing stars of the association. If it was so, this feature would not face to the east, but rather to the south in a symmetrical manner to the south-

⁴ The description of this feature as an “arc-like” is based on the gas emission in the region seen in $H\alpha$ and [O III] mostly from its southern part. In CO and $8\mu\text{m}$ -emission, which dominates its northern part the morphology of this feature is more linear, but still curved, and closer to “arm-like”.

ern arc. Since, this is not the case, the source that triggered star formation in the northern extended feature *should not be the central association, but it should be rather located to the east of the field.*

2.2. A Multi-wavelength Image of NGC 346/N 66

Two X-ray bright features can be seen (in blue) in Fig. 1 (*left*), located to the east and east-northeast of NGC 346 respectively (left part of the image). In this image an extraordinarily good agreement between the northern (upper) X-ray nebula (in blue) and gas presumably photo-ionized seen in [O III] (in green) is present. Although the X-ray emission region appears in Fig. 1 to be small and almost circular, it is actually much more extended, as *Chandra* ACIS observations show (Guerrero & Chu 2008; their Fig. 1c), with its western boundary reaching the northern edge of the bar of N 66, where [O III] emission provides more evidence of heated gas. The northern arc-like nebular feature (seen in green-red) is perfectly outlined by YSOs, IR peaks, and young PMS stars (discussed in § 2.1), and the $8\mu\text{m}$ mid-infrared component of the color image (shown in red) gives further information about dust emission from the star-forming arm. Specifically, its northern part (which includes two PMS clusters and one IR-emission peak), suggests that there is probably still undisturbed cloud material in this part of the region (this is verified by the CO map by Rubio et al. 2000). The location of this part of the star-forming feature as seen in Fig. 1 (*left*) is not compatible with a sequential star formation in the bar of N 66, but rather with a mechanism outside the bar. In order to clarify how this feature may have been actually formed we discuss in the following sections the two most important energy sources known in this specific area.

2.3. HD 5980: A Peculiar Massive Object in N 66

Embedded in the northernmost diffuse X-ray emission of Fig. 1 is a point source centered on the remarkable massive triple system HD 5980, located at $00^{\text{h}}59^{\text{m}}26.55^{\text{s}}$, $-72^{\circ}09'53.8''$ (J2000). This object, which underwent a luminous blue variable (LBV) type eruption⁵ in 1994 is also known as Sk 78 (Sanduleak 1968)⁶. Its spectral variations are unique: Before 1980 this object was classified as WN+OB, then it changed to WN3+WN4 for the period 1980 - 1983, and to WN6 in 1992. In 1994, after the LBV-eruption, it turned to WN11. The high X-ray emission of HD 5980 makes it comparable to the X-ray-brightest single WN stars (Wessolowski 1996) and the brightest WR+OB binaries (Pollock 2002) of the Galaxy. The nature of HD 5980 is investigated in detail with *Chandra* observations of NGC 346 by Nazé et al. (2002), who note that the fast wind from the post-eruptive phase, which collides with the slow wind ejected during the eruption, causes the high X-ray surface brightness. Bright diffuse X-ray emission has been observed in other LBVs, i.e. η Carinae in the Milky Way. However, in contrast to η Carinae, HD 5980 has not had time to develop a LBV nebula around it yet, and so another proposed explanation for the high X-ray luminosity of HD 5980 is the collision of the winds from its close massive stellar components.

Naturally, this massive object may be associated, due to its energetic nature, with the northern feature in the region of

⁵ LBVs are thought to be evolved He-burning stars which may develop into Wolf-Rayet stars.

⁶ The southernmost X-ray bright source is known as Sk 80, and it is a bright massive star classified as O7Iaf (see also Evans et al. 2006).

NGC 346/N 66, and indeed, Walborn (1978) notes that the arcs seen in H α and [O III] are an indication that HD 5980 interacts with its environment. However, from comparisons between X-ray and visible data, Nazé et al. (2002) argue that *the bright, extended X-ray emission around HD 5980 is most probably due to a nearby core-collapse supernova remnant (SNR) whose progenitor is unknown.* These authors describe the shape of this emission as rectangular with an extension to the northeast. Its brightness is rather uniform with the exception of some dark arcs. Its size is $\approx 37 \times 29$ pc. They also note that the spatial coincidence of this extended X-ray emission with the peculiar massive star implies an association between the two objects. We explore this hypothesis in the following section, where the known information about this SNR is presented.

2.4. A Core-Collapse Supernova Remnant in N 66

Massive stars in stellar associations affect their environment by ionizing radiation, stellar winds, and, finally, supernova explosions (e.g. Chu 1997). Massive supernova progenitors do not migrate far from their birthplaces in their short lifetimes, and when they explode the produced shock-waves can trigger cloud collapse, enhancing star formation in the vicinity of their environment. Numerical studies (e.g. Vanhala & Cameron 1998; Fukuda & Hanawa 2000) show that shock-waves with velocities in the range of 15 - 45 km s⁻¹, corresponding to supernova explosions at a distance between 10 pc and 100 pc from the molecular cloud, can induce such a collapse.

Earlier studies show that the general area of NGC 346/N 66 is characterized by at least three known SNRs (Ye et al. 1991; Reid et al. 2006)⁷ located away from the center of the region: SNR B0056-724 (also known as SNR 0056-72.4), located to the southwest of the region, SNR B0056-725 (or SNR 0056-72.5) to the west, and SNR B0057-724 (or SNR 0057-72.2) to the east. The first two SNRs are located to the south and west, outside the field-of-view shown in Fig. 1. The third SNR (B0057-724), though, is located closer to the central part of NGC 346/N 66, and actually *is the SNR associated with the northernmost extended X-ray emission* seen in Fig. 1 (*left*). Indeed, Reid et al. (2006) demonstrated that the extended X-ray emission surrounding HD 5980 coincides exactly with the radio non-thermal emission, confirming “beyond a doubt its true nature as a SNR”.

SNR B0057-724 has been previously studied in H α with echelle spectroscopy by Chu & Kennicutt (1988), who observed high-velocity, shock-accelerated material within the boundary of the SNR that is distinct from the low-velocity quiescent material in the H II region. It was also identified in the radio by Ye et al. (1991), who offer an explanation of why SNRs are expected to be found near the edge of H II regions based on the argument that sequential star formation is expected to occur about 2.5 Myr after and 10 - 15 pc away from the previous generations, as massive stars move away from their birthplaces (Elmegreen & Lada 1977). UV analyses with the *International Ultraviolet Explorer* (de Boer & Savage 1980), *HST* STIS (Koenigsberger et al. 2000), and *Far-Ultraviolet Spectroscopic Explorer* (*FUSE*; Hoopes et al. 2001) have also confirmed the presence of an expanding structure. Danforth et al. (2003) measured the velocity of the SNR

⁷ Reid et al. (2006) suggest the existence of another SNR candidate in the region at $00^{\text{h}}59^{\text{m}}32.4^{\text{s}}$, $-72^{\circ}08'42.4''$ (J2000), based on observations from the DBS 2.3-m telescope at the Siding Spring Observatory.

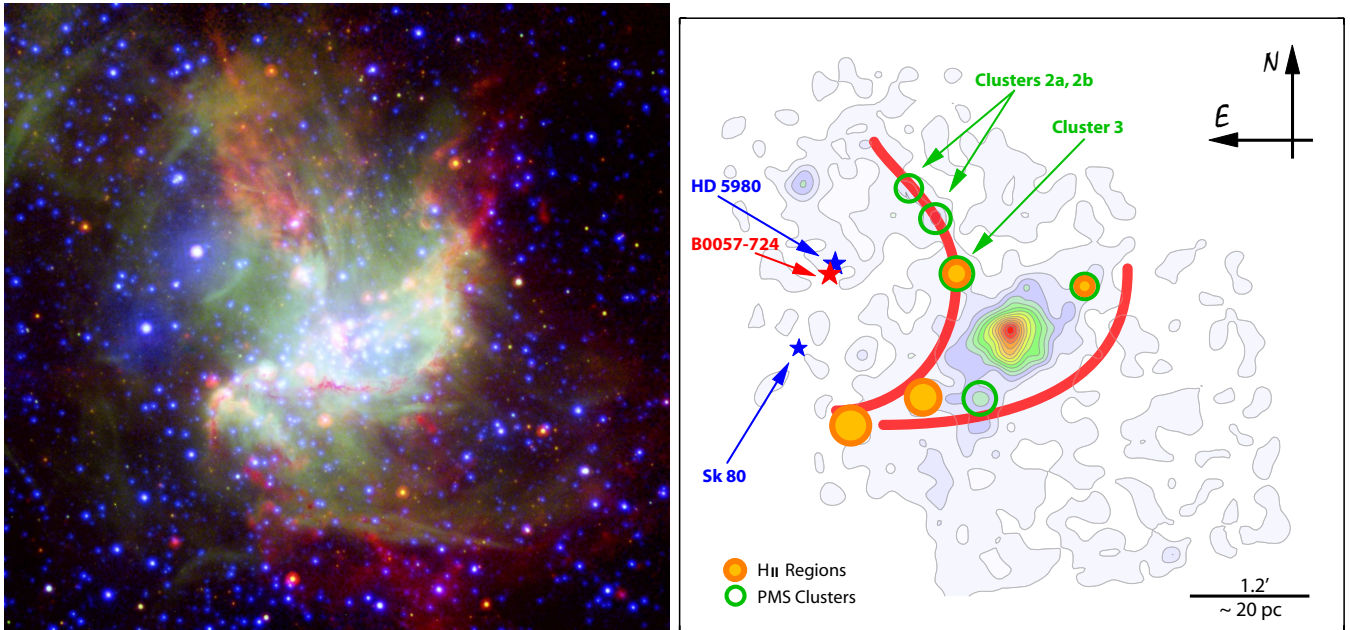


FIG. 1.— *Left*: Color-composite image of the area of NGC 346/N 66 from combination of X-ray observations with XMM-Newton (blue), [O III] (501.1 nm) with NTT (green) and at $8\mu\text{m}$ with *Spitzer* (red). The image covers an area about $6' \times 6'$ ($\sim 100 \times 100 \text{ pc}^2$) wide centered on NGC 346. North is up, East is to the left. *Right*: Schematic representation of the proposed star formation scenario, according to which the massive progenitor of SNR B0057–724 triggered current star formation at the north of the N 66 bar through its wind-blown bubble. The contribution of the most massive stellar object in the area, the LBV HD 5980, is also considered important. The colored iso-density contour map, constructed from star counts of both bright main sequence and faint PMS stars of the region, is shown in the background to demonstrate the geometry of the youngest stellar concentrations. The locations of the SNR, HD 5980, the O-star Sk 80 and significant PMS clusters and H II regions are also indicated. Two important dusty features, also visible in the left panel, are drawn with red thick curves. The one to the south, south-west of the bar of N 66 is considered to be the product of the energy output from the OB stars of the association NGC 346. The other to the north and east of the bar coincides very well with a shock-wave coming from the direction of the SNR B0057–724. The synergy of both these strong energy sources seems to define the recent star formation history of the region.

emission with *FUSE*, and they found high-velocity features with increasing velocity towards the center, across the whole face of SNR B0057–724, *typical for an expanding shell*. The fastest emission ($v_{\text{LSR}} \sim +335 \text{ km s}^{-1}$) is found at about 4 pc south of HD 5980 and is consistent with the peak in X-ray brightness. From X-ray and radio images these authors set the center of the SNR at $00^{\text{h}}59^{\text{m}}27^{\text{s}}$, $-72^{\circ}10'15''$ (J2000).

Danforth et al. (2003) propose a topology, according to which a roughly spherical SNR is located on the near side of N 66, basically closer to us than NGC 346 itself. Consequently the rear side of the SNR is propagating into relatively denser ionized nebula, while the near side is propagating through the more diffuse SMC ISM, and is harder to detect. The X-ray emission arises over a spherical cap, where the shock has encountered and heated the denser material, for which Danforth et al. (2003) estimate a pre-shock density of $\sim 6 \pm 2 \text{ cm}^{-3}$. According to these authors the remnant is not yet even halfway submerged in the N 66 material, and thus, the observed radius of X-ray emission (as observed by Nazé et al. 2002 and seen in the left panel of Fig. 1) is smaller than the actual blast wave radius. HD 5980 and other UV-bright stars in the NGC 346 association are embedded within N 66, but HD 5980 lies behind the remnant, while NGC 346 is outside the SNR⁸.

Danforth et al. (2003) also discuss the relationship between SNR B0057–724 and N 66, and they conclude that the detection of O VI emission together with the $\text{H}\alpha$ kinematics imply the presence of a strong shock in N 66 associated with SNR B0057–724. Although this SN-driven shock affects its direct surroundings, it cannot serve as the triggering mechanism of the observed star-forming event at the north of the bar of N 66

for the following reason. The expansion velocity of the SNR is $v = 175 \text{ km s}^{-1}$ (Danforth et al. 2003). Assuming the Sedov solution for the SNR (e.g. Tang & Wang 2005), the travel time for the shock front to reach the observed star-forming region ($r \sim 18 \text{ pc}$) is $t = 2r/5v = 0.04 \text{ Myr}$, much shorter than the ages of the compact PMS clusters located in the nebular arc, as estimated by us (Paper III; $\tau \lesssim 2.5 \text{ Myr}$), and SSN07 ($\tau \approx 3 \pm 1 \text{ Myr}$). Consequently, while the relative position of the SNR and the east-facing feature seems to support a relation between them (Fig. 1; left) SNR B0057–724 *cannot be* the triggering agent for the star formation in the northern part of N 66. On the other hand, its massive progenitor could have played a very important rôle to this event.

3. A STAR FORMATION SCENARIO

During their main sequence phase massive stars photoionize H II regions or blow bubbles through their winds. Shocks associated with the ionization fronts or expanding bubbles can trigger cloud collapse, and this process lasts for a few Myr, the lifetime of the star during the main sequence phase. Such a process has been observed in the Milky Way, e.g. at the periphery of the H II regions Sh2-219 (Deharveng et al. 2006) and RCW 79 (Zavagno et al. 2006). This mechanism may produce young compact star clusters. Indeed, Lee & Chen (2007) presented recently their diagnosis of the rôle that massive stars play in the formation of low- and intermediate-mass stars in the λ Ori region, Ori OB1, and Lac OB1 associations in the Milky Way. Their study supports the radiation-driven implosion (e.g. Kessel-Deynet & Burkert 2003) as the triggering mechanism, where the Lyman continuum photons from a luminous O star create expanding ionization fronts to evaporate and compress nearby clouds into bright-rimmed clouds. Implosive pressure then causes dense

⁸ Danforth et al. suggest that Sk 80 is probably inside the SNR.

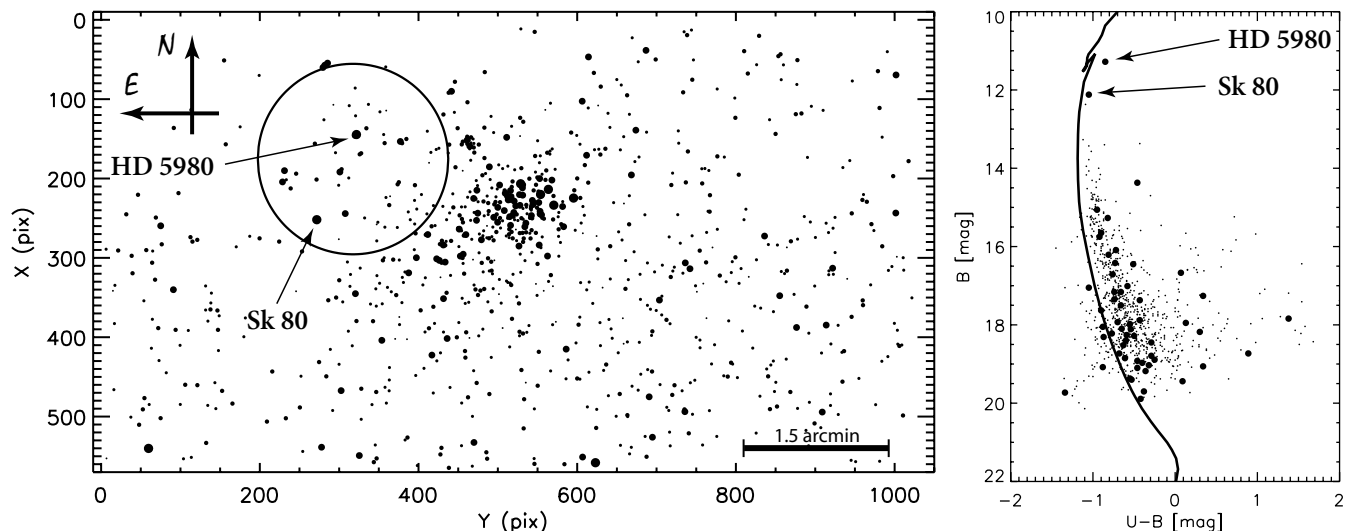


FIG. 2.— Chart of all bright stars in the region of NGC 346/N 66 (left) from photometry with the 0.9-m CTIO Telescope by Massey et al. (1989), and the corresponding $U - B$, B CMD (right). The limits of the bubble as it is outlined by the extended X-ray emission in the area within a radius of ~ 18 pc is also plotted over the stellar chart. The stars included by these limits are plotted with thick symbols in the CMD. The brightest sources in the region of the bubble, HD 5980 and Sk 80, are indicated in both the chart and the CMD. A young isochrone of $\log \tau \simeq 6.6$ (the youngest available) for the grid of evolutionary models by Girardi et al. (2002) with no extinction applied is overplotted on the CMD for an assumed distance modulus of $m - M \simeq 18.95$ mag.

clumps to collapse, prompting the formation of intermediate-mass Herbig Ae/Be (HAeBe) stars somewhat deeper in the cloud and low-mass (T Tauri) PMS stars on the cloud surface (i.e., the bright rim).

Bubbles are formed by the stellar winds, not the ionization energy of massive stars. The expansion of an H II region (not yet a bubble) is caused by its higher thermal pressure due to the high temperature compared to the pre-ionized state. Typical expansion velocities are around 10 km/s at temperatures $\sim 10^4$ K. On the other hand, the expansion of a bubble is driven by the thermal pressure of the shocked stellar wind in the central cavity. The velocity of this expansion ranges from 10 to 100 km/s (Drake 1986), depending on the wind strength and ambient density. When the massive star explodes as a supernova, it explodes inside the bubble blown by itself during its main sequence phase, and the produced SNR will have a size similar to the bubble blown by the star. This will create the picture of a SNR with star formation taking place on its edge, similar to what we observe at the northern part of N 66. However, it is the massive progenitor that triggered star formation and not the SN. The importance of stellar winds as a feedback mechanism to star formation over supernovae has been demonstrated by Leitherer et al. (1992), who present models for the integrated output of mass, momentum, and energy from a concentration of massive stars, computed for typical starburst parameters. In general, the most massive stars evolve from the main sequence (MS) into blue supergiants (BSG) and luminous blue variables (LBV) to become then Wolf-Rayet (WR) stars. Leitherer et al. (1992) found that the (post-main sequence) OB phase, together with the WR phase is the dominant contributor to the total wind output. These authors considered the cases of an instantaneous and of a continuous starburst and they found that in both cases the LBV phase is unimportant, as a consequence of its short life time ($< 10^5$ yr; e.g. Lamers 1989). A total power output between $10^{39.5}$ and $10^{40.5}$ ergs s^{-1} is estimated by these authors for a concentration of stars following a Salpeter IMF with masses between 1 and $120 M_{\odot}$ throughout the epoch of a continuous starburst at $10^6 < T < 10^7$ yr.

3.1. Wind-Triggered Star Formation in N 66

Considering the geometry of the north-northeastern part of the region of NGC 346/N 66 as seen in Fig. 1 (left), the hypothesis of a wind-triggered star formation event seems to explain best the observed recent star formation in this area. We propose a scenario according to which the massive progenitor of SNR B0057–724 has triggered or contributed significantly to the triggering mechanism of star formation through its expanding bubble, producing the northern gaseous arc seen in [O III] and H α . A schematic representation of this scenario is shown in the right panel of Fig. 1, where the two important gaseous features, the southern part of the N 66 bar shaped by the photo-dissociation of the central OB stars and the northern feature delineating the boundary of the SNR X-ray emission, are drawn with red thick curves. If indeed the star-forming northern nebular arc is related to the activity at east, it would be interesting to estimate how much mechanical energy could have been dumped in the area to produce this event.

Naturally the existence of HD 5980 and Sk 80 in the same region with the SNR may not be considered as a coincidence, and therefore one may question if the progenitor is the only triggering agent or not. Indeed, the massive object HD 5980 could contribute to the triggering process through its own bubble blown during its main sequence phase, and another hypothesis is that the cumulative action of even more massive stars in the region, in addition to the SN-progenitor, may have triggered the formation of the northern extended feature. This implies the existence of a massive cluster in the area of the SNR as the triggering agent. In order to test this hypothesis we used the most complete photometric catalog of bright stars in the region (Massey et al. 1989) to search for such a cluster. The stellar chart of all bright sources in this catalog and the corresponding CMD, shown in Fig. 2, indicate that no specific concentration of massive stars can be observed within the bubble limits. Support to the lack of a star cluster of any kind in the region is also provided by the catalog of faint sources down to $V \simeq 28$ mag from our ACS/WFC photometry of the whole NGC 346 region (Paper I), where it can be seen that no specific concentration of low-mass stars exist in the area of the SNR either. It is most probable that the bright stars seen in the

CMD of Fig. 2 belong to the outskirts of NGC 346 itself or to the field. Nevertheless, the only bright sources, which could provide the necessary kinetic energy for a triggered star formation event, in addition to the SN-progenitor, are HD 5980 (Sk 78) and Sk 80, both located within the SNR (Fig. 2).

Single stars between 8 and 20 M_{\odot} produce type II-P SNe when they are red supergiants (Crowther & Smartt 2007). Stellar structure models of more massive stars predict that such stars will have final carbon-oxygen cores of more than 3 M_{\odot} , and hence form black holes (Heger et al. 2003), suggesting that such objects form very faint SNe. Recent discoveries suggest that very massive stars may explode as SNe in their LBV stage. Pastorello et al. (2007) found that the very energetic SN2006jc was a type Ic event, but embedded within a He-rich circumstellar envelope and that it was coincident with an LBV-like outburst just 2 yrs before collapsing. According to these authors it could have been an originally very massive LBV which lost the last of its H and He envelopes in energetic mass ejection episodes and collapsed as a stripped Wolf-Rayet star. Recently Smith et al. (2007) reported the analysis of the most luminous SN ever recorded, the type II_n SN2006gy in NGC 1260, which reached an absolute magnitude of $R \simeq -22$ mag. The combination of optical and X-ray monitoring suggests it was the explosion of a very massive star of about 100 M_{\odot} , which failed to shed its hydrogen envelope. According to these authors SN2006gy implies that some of the most massive stars can explode prematurely during the LBV phase, never becoming Wolf-Rayet stars.

Since there is no information about the nature of the progenitor of SNR B0057–727, and in order to have an upper-limit estimation of the wind-blown energy expected by it, we may assume that this progenitor was an object as massive as the estimate of Smith et al. (2007) for SN2006gy, meaning roughly an early O-type BSG. Typical ionizing photon fluxes for such stars are $F_{Ly} \simeq 10^{50}$ UV photons s^{-1} (Vacca et al. 1996; Schaerer & de Koter 1997). O-type stars have mass-loss rates \dot{M} of about 10^{-7} - 10^{-5} $M_{\odot} yr^{-1}$ and terminal velocities v_W in the range $1 - 4 \times 10^3$ km s^{-1} (Chlebowski & Garmany 1991; Lamers et al. 1995), thus injecting large amounts of energy to the neighboring ISM. The corresponding mechanical luminosity can be derived as $L_W = \dot{M}v_W^2/2$ (e.g. Cappa & Benaglia 1998). Consequently, an O3-type star with a mass loss rate of 10^{-5} $M_{\odot} yr^{-1}$ and a wind velocity of 3750 km s^{-1} (Puls et al. 1996) would have a stellar wind mechanical luminosity of 4.5×10^{37} ergs s^{-1} . This mechanical input is lower than the assumed energy contribution of a massive cluster in the models by Leitherer et al. (1992), but since the density of the original cloud is unknown, one can only speculate about the energy that would be needed to trigger star formation in the region. Nevertheless, the two additional energy sources in the region should be also considered. Sk 80, being an O7 I giant would contribute around 3×10^{36} ergs s^{-1} (Puls et al. 1996).

HD 5980 has been suggested to be a triple system (Koenigsberger et al. 2000) with the first component being a 50 M_{\odot} WN6 star, the second a 28 M_{\odot} WN2 (with high uncertainty) and the third component being a O4 - O7 giant. Koenigsberger et al. (2000) found that a wind-wind collision shock cone winds tightly around the second companion, and using the relation given by Volk & Kwok (1985), under a two-wind approximation, they provide a rough estimate of 2×10^{-4} $M_{\odot} yr^{-1}$ for the current mass-loss rate of the system with a terminal velocity of ~ 2000 km s^{-1} . This mass-

loss rate measurement, which is higher than typical rates of Galactic WR stars ($2 - 10 \times 10^{-5}$ $M_{\odot} yr^{-1}$ with terminal velocities of 1000 - 2500 km s^{-1} ; van der Hucht 1992), yields a mechanical luminosity of 2.6×10^{38} ergs s^{-1} for HD 5980. As far as the ionizing flux of HD 5980 is concerned, Law et al. (2002) found that the Lyman continuum flux of WN stars appears to be independent of spectral type, and lower bound estimates tend to cluster around 10^{48} UV photons s^{-1} . This would be the ionizing energy contributed by each of the WN components of HD 5980, while the third component, being an O4 - O7 giant, would provide an additional $\sim 10^{49.5}$ UV photons s^{-1} .

From the mechanical luminosities of each of the involved objects in the region, one can estimate that the total mechanical power that was supposedly dumped in the region is of the order of that produced by HD 5980 alone, $L_W^{Tot} \simeq 3 \times 10^{38}$ ergs s^{-1} , implying a small contribution from the massive progenitor of SNR B0057–724 and Sk 80 in the process. However, this result stands only if the SN-progenitor did not go through a major mass-loss event. According to the standard evolution of O-type stars with masses $\gtrsim 60$ M_{\odot} , these stars will go through a WNH or LBV phase that removes via line-driven winds the remaining H-envelope to yield a $\lesssim 20$ M_{\odot} WR star. Moreover, the large number of observed giant eruptions of LBVs, which can remove around 10 M_{\odot} in a few years (Smith & Owocki 2006), clearly suggests that massive O-type stars do not shed most of their initial mass by the end of the main sequence phase, but there is still enough mass remaining to power major mass-loss during the WNH or LBV phase. Indeed, recent observational evidence suggests that mass-loss rates for O stars need to be revised downward (Smith 2007), in line with recent observed mass-loss rates for clumped winds (e.g. Fullerton et al. 2006).

Could the progenitor of SNR B0057–724 have lost most of its initial mass via an eruptive mass-loss event (during e.g. a LBV phase), triggering the observed star formation? The answer is positive. The primary star in the η Car system, which is suggested to have a present-day mass $\gtrsim 100$ M_{\odot} has lost 20 - 30 M_{\odot} , in violent LBV eruptions in just a few thousand years (Smith et al. 2003), in addition to its steady wind. Consequently a SN-progenitor alone is capable of triggering star formation event, as has been recently observed with the *AKARI* infrared satellite by Koo et al. (2008). These authors report the discovery of a star-forming loop around the young, Crab-like SNR G54.1+0.3 in the Galaxy, and they propose that star formation was triggered by the progenitor star of G54.1+0.3, which has a mass of $\lesssim 15$ M_{\odot} . The triggering must have occurred near the end of the progenitor's life, possibly after it had evolved off the main sequence. Under these circumstances, the massive progenitor of SNR B0057–724 alone may have provided the necessary mechanical energy to trigger star formation to the north, while the contribution of HD 5980 may have significantly enhanced this event.

3.2. Gas Kinematics in the Area of the SNR

Additional information on the interstellar environment of SNR B0057–724 can certainly be provided by the kinematic study of the surrounding gas. In Fig. 3 we show a set of images centered on NGC 346/N 66, constructed from observations of atomic and ionized gas. The observations from the neutral hydrogen emission survey of the SMC constructed with the *Australia Telescope Compact Array* (ATCA) and *Parkes Observatory* at the *Australia Telescope National Facil-*

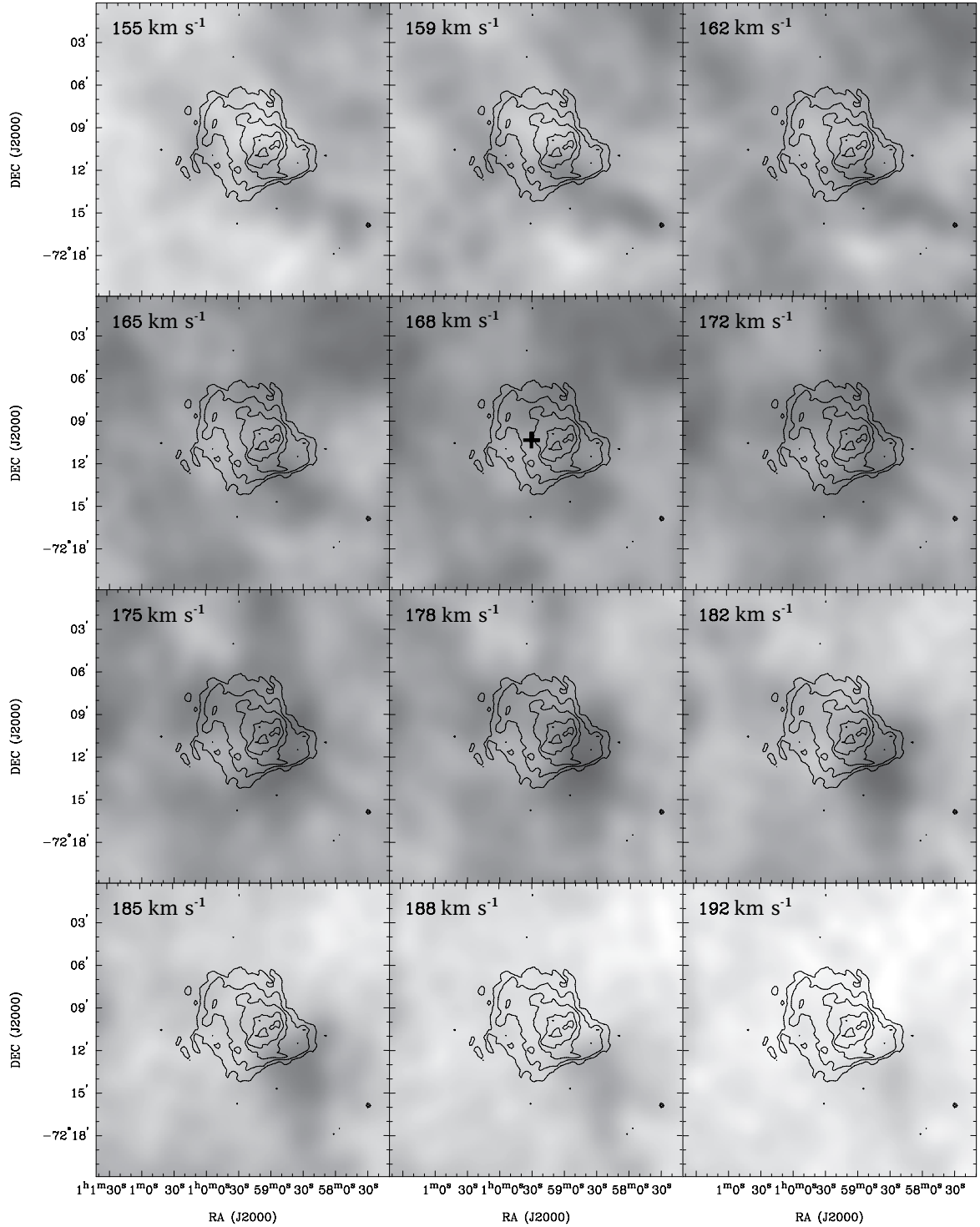


FIG. 3.— Images of the region of NGC 346/N 66 from the H I mosaic constructed with *ATCA* and *Parkes* (greyscale) with the H α + continuum from MCELS overlaid (contours). The most significant velocity planes are shown, with the corresponding heliocentric velocity indicated on the top-left corner. Each image covers an area about $0.35^\circ \times 0.35^\circ$ ($\sim 357 \times 357 \text{ pc}^2$) wide, centered on N 66, which is indicated by the H α isopleths. North is up, East is to the left. The thick cross-symbol in the image of the 168 km s^{-1} velocity plane indicates the position of SNR B0057–724. A hole in the H I east of N 66 and possibly related to the area of the SNR can be seen in the velocity planes between 165 and 178 km s^{-1} , with its larger extent seen in the 168 km s^{-1} velocity plane. This velocity coincides almost perfectly with the systematic velocity of the SNR found with echelle spectroscopy by Chu & Kennicutt (1988), indicating that the neutral hydrogen is possibly kinematically related to the ionized gas.

ity (ATNF) are shown as greyscale images⁹ (Staveley-Smith et

⁹ *Parkes* single-dish observations were combined with an aperture synthesis mosaic of 320 separate pointings of the 375-m array from *ATCA* interferometry. These observations are sensitive to angular scales between $98''$ (30 pc) and 4° (4 kpc) over a field of 20 deg^2 with velocity channels $\sim 1.65 \text{ km s}^{-1}$ wide, spanning between heliocentric velocities of ~ 88.5 and

al. 1997; Stanimirović et al. 1999). The original data-cubes were kindly provided by Snezana Stanimirović. Overplotted are the contours from the H α image of the same general area of N 66 obtained within the *Magellanic Cloud Emission Line* $\sim 215.5 \text{ km s}^{-1}$.

*Survey*¹⁰ (MCELS; Smith et al. 2000). Only isopleths, which correspond to intensity higher than 3σ above the background, where σ is the standard deviation of the background noise, are shown.

In Fig. 3 the 12 most significant velocity planes from the HI interferometric data between 155 and 192 km s^{-1} (heliocentric velocities) are shown. Each plane is 3.3 km s^{-1} wide and it is the average of two planes in the processed cube. The central compact H α concentration in each image is the nebula N 66 and the area of the SNR is directly to its left (east). It is very interesting to see that from these sequential images, indeed, *a possible relation between the gas kinematics and the area of SNR B0057–724* is revealed through *a gas bubble visible in the planes between 165 and 178* km s^{-1} . However, the hole seen in H I seems to be much larger than the SNR itself, which is about $2'$ in diameter (Chu & Kenicutt 1988). This implies that this hole should have been blown also by HD 5980 and perhaps with the help of other stars. It should also be mentioned that the location of the SNR is at the edge of the H I hole, not its center. From the quantitative point-of-view, the echelle data of Chu & Kenicutt (1988) indicate a systemic velocity for the SNR of $v_{\text{LSR}} \sim 158$ km s^{-1} , which translates to heliocentric velocity of $v \approx v_{\text{LSR}} + 11$ $\text{km s}^{-1} \simeq 169$ km s^{-1} . This value *is in very good agreement with the velocity plane where the hole in the atomic gas at the area of the SNR is more clearly visible* in the images of Fig. 3 (velocity of 168 km s^{-1}). This result provides evidence that indeed the atomic gas *is possibly kinematically related to the ionized gas and therefore possibly to the SNR*.

However, it is not clear whether the H I hole, seen at 168 km s^{-1} , is indeed a bubble. In order to clarify if this hole actually represents an H I bubble, we examine the spatio-kinematic structure of the neutral hydrogen in the vicinity of N 66 by constructing position-velocity (PV) diagrams. Each PV diagram consists of an east-west slice (slit) through the H I data cube where we have averaged over $1'$ in the north-south direction. Multiple PV diagrams were constructed, each after stepping sequentially by $1'$ in the north-south direction to cover the whole area of N 66 from east to west. Twelve PV diagrams are shown in Fig. 4, where the positions of the corresponding slits are overlaid on the maps of the area in H α (from MCELS) and H I (from ATCA and Parkes). The vicinity of N 66 is fully covered in the H α image, the features of which are easily comparable to the color-composite image of Fig. 1. The star-forming feature north of the bar of N 66 is also easily detectable in this map. Above this feature, at slit position 07, the H I velocity does not show any split. At slit position 08, though, the H I at ~ 170 km s^{-1} starts to split, and further south, this velocity split becomes more clear, giving possible evidence of an expanding shell-structure. The PV diagrams of Fig. 4 indicate an expansion velocity of ~ 10 km s^{-1} . It is interesting to note that the line split does not occur over N 66, at slit positions 08 and 09. This indicates that N 66 does not seem to be responsible for the expanding shell.

Considering a distance of 60 kpc and a correction factor for He of 1.4 we integrated the H I column density over an area roughly $12' \times 12'$ wide, centered on the shell, between velocities of 158 and 188 km s^{-1} and derived a total mass of $1.52 \times 10^6 M_{\odot}$ in the H I expanding shell. This mass corresponds to a total kinetic energy of about 1.5×10^{51} erg.

¹⁰ MCELS is accessible at <http://www.ctio.noao.edu/mcels/>

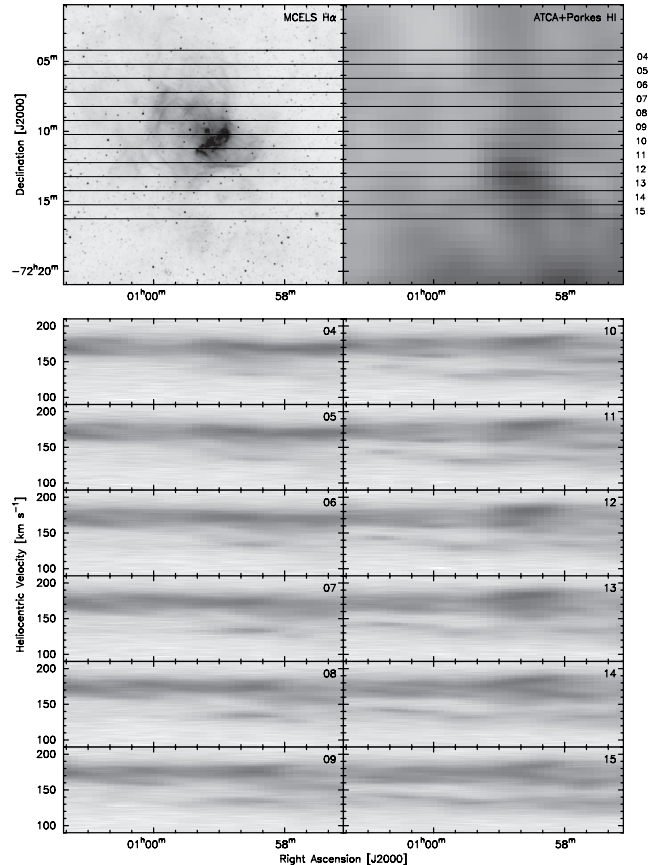


FIG. 4.— Position-velocity diagrams from ATCA and Parkes HI observations for 12 selected slits covering the whole area of N 66 from east to west (long-slit spectra). The positions of the slits are shown on the maps of the area in H α (from MCELS) and HI (from ATCA and Parkes). The HI velocity of ~ 170 km s^{-1} shows a split at slit position 08 and southwards, indicating that the shell probably expands. This expanding shell structure continues south.

Taking into account the total mechanical power estimated in § 3.1 for the SN-progenitor, HD 5980 and Sk 80 (equal to 3×10^{38} erg s^{-1}), one can see that these objects have dumped a larger amount of mechanical energy than the estimated kinetic energy in the shell in less than 1 Myr. Indeed, it seems that it is typical for expanding bubbles that the kinetic energy retained in the shell is only a small fraction of the total stellar energy injected. This is observed for example in the superbubble N 51D in the Large Magellanic Cloud, where the H I kinetic energy is found to be almost an order of a magnitude lower than the total stellar wind and supernova energy input (Chu et al. 2005). Based on our calculations of § 3.1, the total energy provided by the SN-progenitor, HD 5980 and Sk 80 for the last couple Myr is indeed an order of a magnitude higher than the kinetic energy in the shell.

4. FINAL REMARKS

In conclusion, based on the evidence presented here, we propose an expanding H II region or bubble blown by the winds of the massive progenitor of SNR B0057–724, possibly the massive object HD 5980 and maybe the O7 giant Sk 80 - all located at the eastern vicinity of NGC 346/N 66, as the secondary mechanism that shapes the recent star formation in this region, in addition to the photo-ionizing process of the OB stars of the association. This mechanism is similar to shell-like H II regions, with a central young cluster in an evacuated cavity, and with ongoing star formation triggered around their periphery, and therefore is a rather quiescent

process. Typical examples for such regions in the MCs are LH 9/N 11 (Walborn & Parker 1992) and 30 Doradus (Walborn et al. 2002) in the LMC and NGC 602/N 90 (Gouliermis et al. 2007; Carlson et al. 2007) in the SMC. It should be noted, however, that within the X-ray bubble associated with the SNR, which most probably outlines the wind-blown bubble of its progenitor, no signature of any underlying cluster is found.

The induced star formation in this part of the region of NGC 346/N 66 is evidenced by the existence of PMS clusters, candidate YSOs and IR-emission peaks at a projected distance ~ 18 pc and possibly at even larger distances from the X-ray bubble. All these objects are preferably located in an extended feature north of the bar of N 66, which is outlined by the emission from the gas, observed in $H\alpha$ and [O III], as well as from the dust, as it is seen in CO, H_2 and $8\mu\text{m}$ maps. Lee & Chen (2007) findings in the λ Ori region, Ori OB1, and Lac OB1 associations suggest that intermediate-mass HAeBe stars are formed in the denser parts of the cloud, while the low-mass T Tauri stars are formed at the outskirts near the photo-evaporating cloud layers. Our photometry in $H\alpha$ (Paper III) showed that indeed stars with $H\alpha$ -excess (signature of candidate HAeBe stars) are located in the area of the northern compact PMS clusters. Based on the aforementioned observations in different wavelengths, the extended feature north of the bar of N 66, which hosts this star formation, may be considered as part of a large arc centered on the SNR (Fig. 1 *right*), which extends also to the south and in the bar. In this case, one may conclude that its northern part is projected closer to us, outside N 66, since the dust is well outlined by the $8\mu\text{m}$ emission (seen in red in Fig. 1; left), while its southern part is embedded *in* the nebula (as suggested by the schematic of Fig. 1; right).

On the other hand, considering that the northern part of this feature as seen in CO and IR maps appears to be more linear with small curvature (see e.g. maps by Contursi et al. 2000; Rubio et al. 2000; Simon et al. 2007), one may argue that it may not bear a morphological connection to the triggering sources to the east. Against this argument stands the fact that this linearity is confined only in the northernmost part of the structure, while its southern part shows a curvature to the east, and fits very well to the alignment of emission from both gas and dust towards the south (see e.g. maps by Contursi et al. 2000; Rubio et al. 2000; Simon et al. 2007; Paper III). The latter appears to be well related to the positions of the H II regions and IR peaks, which are located *in* the south-eastern part of the bar of N 66. Consequently, the northern feature can be considered to be extended to the south and to become *embedded* in the south-eastern part of the bar, forming a large arc-like feature, which covers the whole eastern part of N 66 nebula (Fig.1), and which is centered on the SNR. Further support to this argument provides the outstanding coincidence of this arc structure and the non-thermal emission related to

the SNR B0057–724, shown in the $H\alpha$ and [S II] continuum-subtracted images by Reid et al. (2006; their figures 1 and 2). Under these circumstances the dust emission from the northernmost linear part of the structure may not come from only a “strip” of molecular material, but from a whole curved surface of the wind-blown bubble, projected in front of the bar of N 66. It should be noted, though, that an equally valid description of the morphology of the $8\mu\text{m}$ emission is that of a partial arc with mild curvature pointing west, which appears connected to the N 66 bar through a clump of emission.

In any case, the proposed scenario draws the picture of a unique case of complexity in the star formation history of NGC 346/N 66, the brightest H II region in the SMC. According to this scenario it is the collaborative (or competitive) action of two major energy sources that shapes the current star formation process in this extraordinary region. The first source, located at the center of the nebula N 66, is the bright stellar content of the association NGC 346 and affects mostly the bar of the nebula. The second source, located at the eastern part of the region, is associated with the bright X-ray bubble of a SNR. We propose that the massive progenitor and possibly two other massive stellar objects have triggered the most recent star formation at the northern part of the region away from the bar of N 66 within that last few Myr. Observations of the gas kinematics provide further support to this hypothesis. Under these circumstances, the identified compact PMS sub-clusters in the region *cannot* all be the product of spontaneous cloud collapse and fragmentation (see e.g. Elmegreen & Lada 1977). They are rather the product of star formation inside *and* outside the bar of N 66, induced by wind-shock waves (e.g. Vanhala & Cameron 1998) or ionization shock fronts (e.g. Kessel-Deynet & Burkert 2003) driven by OB stars into the surrounding cloud.

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