Rev. Mexicana Astron. Astrof., **18**, 105-113 (1989)

SUPERNOVA REMNANTS AND BUBBLES IN THE LARGE MAGELLANIC CLOUD

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RESUMEN. En este trabajo se analizan los resultados de las observaciones de tres complejos nebulares en la Nube Mayor de Magallanes realizadas con un interferómetro Fabry-Pérot de barrido. Estas observaciones, de alta sensibilidad y de alta resolución espacial nos permiten tener una mejor comprensión del origen y de la evolución de estas nebulosas. Además, este tipo de observaciones permite el descubrimiento de estructuras a pequeña escala.

ABSTRACT. The results of the observations of three nebular complexes in the LMC with a scanning Fabry-Perot interferometer are discussed in this work. These high sensitivity and high spatial resolution observations allow us to understand better the origin and evolution of these nebulae. Small scale structures are easily discovered by using this method.

Key words: **GALAXIES– MAGELLANIC CLOUDS — INTERSTELLAR–BUBBLES — STELLAR–SUPERNOVAE REMNANTS**

I. INTRODUCTION

The photographs of the Large Magellanic Cloud (LMC) (see for example the H_α + [NII] Schmidt plate of Davies *et al.* 1976) show that there are a large number of ring-shaped nebulae in it with diameters between 10 and 200 pc (at the LMC distance). These nebulae are known as bubbles and they are the subject of this comunication. The LMC photographs also reveal the existence of large diameter filaments; it is known that those filaments are arranged in spherical shells: the supergiant shells (SGSs), discovered by Meaburn (1980), of diameters from 300 pc to 1 kpc. It is thought that bubbles and SGSs have different origins, at least in scale.

The bubbles have often a young stellar association inside them and sometimes the bubbles are located at the boundaries of the SGSs. The bubbles do not form a homogeneous class of objects. Indeed, they could have different origins such as SN explosions or stellar winds.

The main characteristics of the bubbles in the LMC as well as the comparison of their properties with the galactic ones have been studied in a previous work (Rosado, 1986). That work showed that in the LMC the SNRs with diameters larger than 10 pc, do not evolve following the adiabatic phase as do the galactic SNRs (Lozinskaya 1980) but instead they seem to evolve in agreement with one of the following possibilities: the adiabatic evaporative phase of the models of McKee and Ostriker (1977), the evolution in a medium of decreasing density (Cox and Franco 1981) or the evolution following the laws of a wind driven shell (Tenorio-Tagle *et al.* 1988). It is interesting to note that for this latter case the SN explosion must have occurred in a pre-existing cavity blown by stellar winds.

Regarding the wind-driven bubbles, the work of Rosado (1986) shows that presumed wind-blown bubbles in the LMC (from the sample chosen on the basis of the stellar content and kinematics of the bubbles) seem to evolve following the predictions of momentum conserving models instead of those of the classical energy conserving models

(Dyson and de Vries 1972; Weaver *et al.* 1977). This result agrees with the conclusions of Treffers and Chu (1982) for the type W nebulae around WR stars in the galactic case. However, these results have been recently revised for the galactic WR nebulae due to new observations and theoretical work (Marston and Meaburn 1988; Smith *et al.* 1988; Dufour 1989).

Other studies concern the mechanisms of star formation in the SGSs and bubbles as well. Sequential star formation from the center to the periphery of SGSs has been found by Dopita *et al.* (1985). These authors find that the bubbles located at the edges of the SGSs were associated with the youngest component. Detailed studies of the ages of stellar associations inside the bubbles and of their morphology have revealed that sequential star formation is found even at the scale of large diameter bubbles (Lortet and Testor 1988).

Finally, it was found that the bubbles are associated with one or more extensive HI sheets of different velocities (Meaburn *et al.* 1987).

The study of bubbles in the LMC presents the following difficulties:

— A poorer spatial resolution for a given instrument than the galactic case due to the larger distance to the LMC.

— Poor knowledge of the stellar content of a given bubble. Indeed, the catalogues of early type stars in the LMC are not complete because it was found that the earliest stars are often associated with larger local IS reddening, which makes them fainter.

— Poor angular resolution of the radio data.

On the other hand, the study of bubbles in the LMC offers the following advantages:

— A global view of several types of bubbles and their locations and interactions can be obtained.

— All of the objects are almost at the same (and known) distance.

— The interstellar absorption between the LMC and the observer is low and relatively constant.

— The possibility of comparison between the LMC bubbles and the galactic ones in order to identify the characteristics of bubbles that are related with the global properties of the host galaxy.

— It is a preliminary step; this study can be extended to more distant galaxies.

In what follows the first results in the study of bubbles in the LMC with a sensitive, high spatial resolution scanning Fabry-Perot interferometer are shown. The work has been done by Jaques Boulesteix, Yvonne and Yvon Georgelin, Annie Laval, E. Le Coarer and Michel Marcelin from the Marseille Observatory, France, Guy Monnet from the CFH Corporation and Margarita Rosado from the Instituto de Astronomía, UNAM, México.

II. MAIN CHARACTERISTICS OF "CIGALE"

The characteristics of the equipment used in the observations discussed below have been described in Boulesteix *et al.* (1983) and are the following:

— CIGALE is a scanning Fabry-Perot (FP) interferometer coupled with a two-dimensional photon counting system.

— The free spectral range of the FP interferometer corresponds to 376 km s^{-1} at H_{α}.

— The scan is produced in 21 steps (each one of 20 s exposure). The total exposure time contains a number of identical scanning cycles.

— The spatial resolution is $2''.6$ per pixel (equivalent to 0.7 pc per pixel at the LMC distance) and could be increased by a factor of two.

— The field of view is a square of $7'$ side.

— The scans produce "λ-maps" which are successive monochromatic images of the object through narrow λ bands ($\delta v = 18.8$ km s^{-1}).

— The velocity accuracy is better than 2 km s^{-1} for signals with high S/N.

— An H_α brightness of about 10^{-6} erg cm^{-2} s^{-1} sr^{-1} can be reached with 10 min exposure time and S/N < 2.

III. FIRST RESULTS OF CIGALE OBSERVATIONS OF BUBBLES IN THE LMC.

In preceding works we have studied 43 regions in the LMC with photographic imagery in H_α and [SII] lines and photographic fixed gap FP etalon in H_α (Georgelin ***et al.*** 1983; Rosado ***et al.*** 1981, 1982). Now, with the higher spatial resolution and higher sensitivity of CIGALE a sample of bubbles of different types were selected to be observed with this equipment. In the following the main results obtained on N62B (a stellar wind blown bubble), N186D (a SNR), N186E (a large diameter bubble) and N120 (a complex of bubbles and a SNR) are presented.

III.1. N62B.

This nebula has been studied by Laval ***et al.*** (1987a), here we report on the main conclusions derived by these authors. Figure 1 is a reproduction of Fig. 5 of Laval ***et al.*** (1987) which shows the image in H_α of this nebula.

Fig. 1. Cigale image in H_α of the nebula N62B. North is at the top, East is at the left. (Reproduced from Laval *et al.* 1987).

As one can see, the nebula is semi-spherical exhibiting few filaments. An O7.5I star (SN 152-66) seems to be the responsible for the formation of this bubble; this star shows P Cygni profiles in its UV spectrum.

— The kinematical data are consistent with an expansion of the order of 35 km s^{-1} in an inhomogeneus medium.

— The H_α surface brightness suggests a gradient in the rms electron density ranging from 0.3 to 1 cm^{-3}.

— We are probably seeing the joint action of a stellar wind and the encounter of the edge of a neutral cloud. The shell is then expected to burst towards the direction of lower density (Tenorio-Tagle *et al.* 1979; Franco 1989).

— Six bright condensations were discovered in the shell with diameters about 5″ (2.2 pc).

III.2 THE COMPLEX N186.

This complex is composed of the SNR N186D and the bubble N186E. The SNR is located at the northern edge of N186E. The H_α photograph of Meaburn *et al.* (1984) reveals the filamentary appearence of both N186D and N186E. While N186D is a well known SNR, N186E has a controversial origin. This complex is located in a region where extended (~ 500 pc) HI sheets were discovered (Meaburn *et al.* 1984). These sheets have different heliographic velocities over a range from 142 to 380 km s^{-1}. The early-type stars reported in the catalogues that could be inside

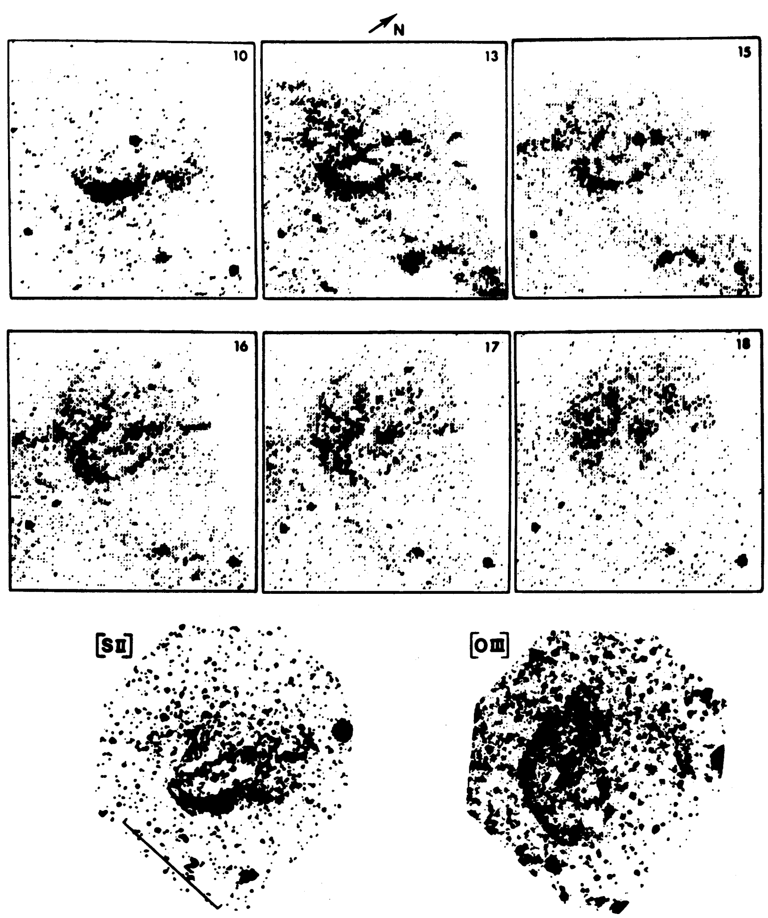

Fig. 2. Radial velocity field (λ-maps) and photographs in [SII] ($\lambda\lambda$6717 – 6731 Å) and [OIII] ($\lambda\lambda$4959 – 4007 Å) of the SNR N186D. (Reproduced from Laval *et al.* 1989a).

this complex are: SN 30a-70 (B1:), SN 32-70 (B0 I, but in UV it does not show evidence of winds) and SN 30-70 (B5 I) (Rousseau *et al.* 1978). However, in an exhaustive search for other early type stars, Greve *et al.* (1988) have discovered other possible early type stars based on their photometry, in particular, Gr3, which seems to be either an O4 star or a tight association of young stars. It is seen that the UV flux of Gr3 is enough to ionize the whole N186E. It is interesting to note that none of the early-type stars is in the centre.

The results of the CIGALE observations on this complex (Laval *et al.* 1989a; Rosado *et al.* 1989) are the following:

— Both nebulae (D and E) are located in the same HI sheet, thus their proximity is not a projection effect.

— The expansion of N186D is not spherically symmetric. Indeed, Figure 2 (Fig. 2 of Laval *et al.* 1989a) shows the λ–maps corresponding to this SNR.

For this object we see a complete spatial separation between the zones of large approaching velocities (the SW filament; $v_r \cong 150$ km s^{-1}) and the zone of large receding velocities (the NE zone; $v_r \cong 340$ km s^{-1}). This separation cannot be explained in terms of the expansion of a spherically symmetric shell. Instead, our kinematical data are more in agreement with an expansion of two fragments of a spherical shell. One of these fragments (the SW filament) seems to be in interaction with N186E.

— We derive the following parameters for the SNR N186D by assuming that it is in the radiative phase of evolution (Chevalier 1974) and that the same relations hold even if the SNR is not spherically symmetric:

$$R = 20 \text{ pc} \qquad V_{exp} = 90 \text{ km s}^{-1} \qquad n_0 = 2.8 \text{ cm}^{-3}$$

$$E_0 = 1 \times 10^{51} \text{ ergs} \qquad t = 6.5 \times 10^5 \text{ yr}$$

— We detect two bright condensations inside the SW filament, at 240 and 170 km s^{-1} respectively. Figure 3 (Fig. 7 of Laval *et al.* 1989a) shows the profiles over the detected condensations. Another intense knot (diameter 1 pc) has been detected coincident in position with the stellar association Gr3.

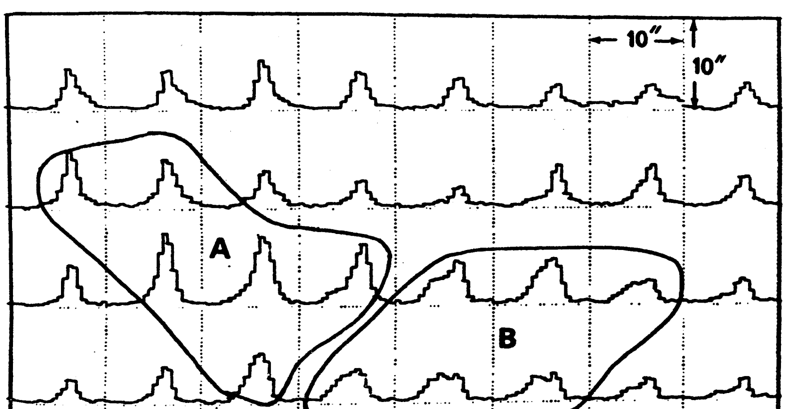

Fig. 3. Radial velocity profiles of the condensations located inside the SW filament of N186D. (Reproduced from Laval *et al.* 1989a).

— The bubble N186E has velocity profiles contaminated by two very faint components possibly associated with two HI sheets that are partially photoionized (at 180 and 300 km s^{-1}). However, an expansion motion can be discriminated with $V_{exp} = 25$ km s^{-1}.

— The filamentary appearence of this roughly spherical nebula as well as the lack of a central early-type star suggest that it could be a fossil SNR photoionized by Gr3.

— In that case, N186E would also be in the radiative phase of evolution and we derive the following parameters for this presumed SNR:

$$R = 53 \text{ pc} \qquad V_{exp} = 25 \text{ km s}^{-1} \qquad n_0 = 0.8 \text{ cm}^{-3}$$

$$E_0 = 1 \times 10^{51} \text{ ergs} \qquad t = 6.5 \times 10^5 \text{ yr}$$

— If N186E is really a SNR then we have the interesting case of two SNRs in interaction. The interaction of SNRs has been proposed as a mechanism of formation and development of tunnels of hot gas in the ISM (Cox and Smith 1974). There are theoretical models of interacting SNRs (Ikeuchi 1978; Jones *et al.* 1979) which unfortunately cannot be applied directly to this case. However this interaction could explain the asymmetry found in the kinematics of N186D and also the origin of the knots discovered in the SW filament which corresponds to the zone of interaction of both SNRs. Indeed, the knots found in the zone of interaction could be the result of Rayleigh-Taylor instabilities developing there.

III.3 THE COMPLEX N120.

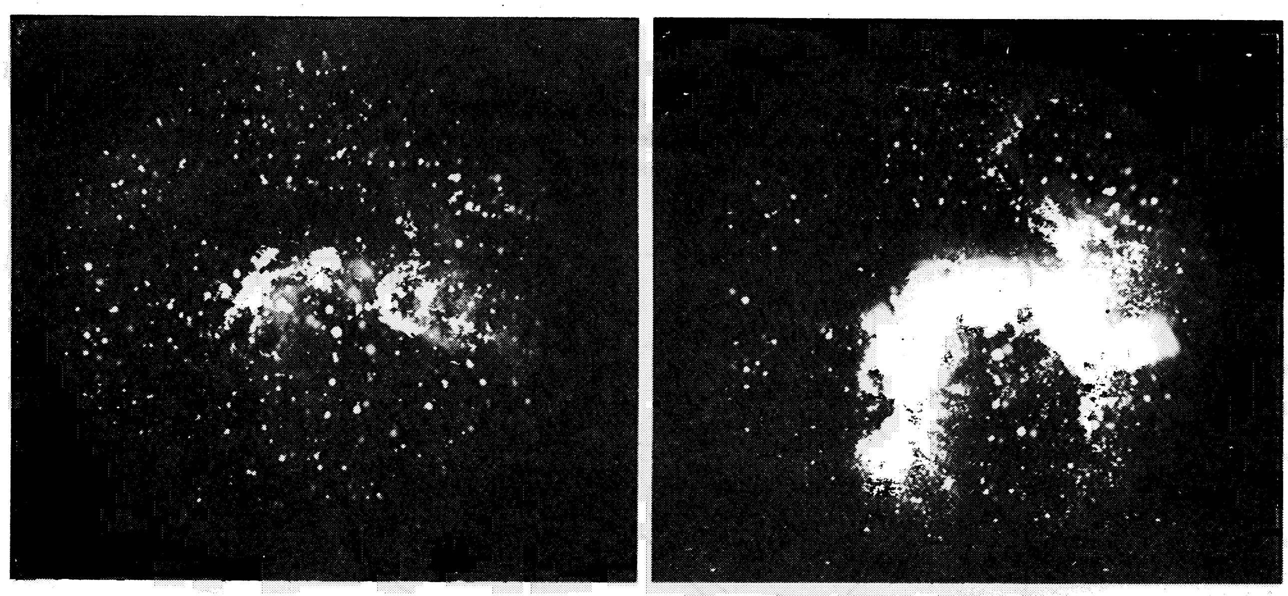

Fig. 4. Photographs in [SII] ($\lambda\lambda$6717 Å) (top) and H_α (bottom) of N120. North is at the top, East is at the left. (Reproduced from Georgelin *et al.* 1983).

Figure 4 shows a [SII] and a H_α photograph of N120 (Fig. 1k of Georgelin *et al.* 1983). From this image we can see the structure of the complex which appears to be composed of several different small bubbles conforming an arc of larger diameter. The bubble of high [SII] emission is the SNR N120. Condensations A and B are marked in this figure.

Here, some results of the CIGALE observations on condensations A and B are mentioned. We would refer to Laval *et al.* (1989b) where the study of the whole complex is given.

We have observed this region earlier with a photographic FP (Georgelin *et al.* 1983), and we did not detect large motions for the condensations A and B. The observations with the CIGALE reveal that both zones show violent motions.

Condensation A has a central star (BI141) catalogued in Rousseau *et al.* (1978) as a B1-2 star. A spectrum obtained at ESO classifies it as a BI1b star (A. Laval, private communication). Our kinematical results reveal a bubble structure (diameter $\simeq$ 8 pc) not noticeable on the photographs. Figure 5 shows the velocity distribution of "scans" in the X direction of the XY pixel grid of the detector . It is evident that large splittings appear in the central regions around the star BI141. The maximum velocity difference amounts to 100 km s^{-1}.

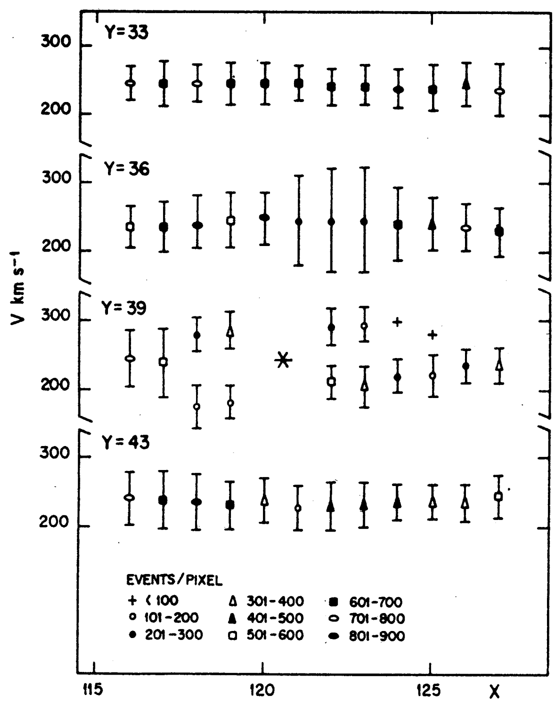

Fig. 5. Velocity distribution of "scans" in the X direction of the condensation A of N120. The different symbols represent the different intensities. The bars represent the broadennings of the profiles.

Condensation B (diameter $\simeq$ 2 pc) also shows violent motions but less extensive than condensation A. One faint star, of unknown spectral type, is embedded inside the knot.

IV. CONCLUSIONS.

— High spatial resolution, high sensitivity observations allow us: to study better the components of the velocity profiles, to reach —with high S/N ratio— the central parts of the bubbles (fainter than the edges) and thus, to detect expansion motions, as well as to study small scale structures, which are easily discovered in the λ–maps.

— With this type of observations we have discovered some interesting common features in the observed regions:

a. The existence of small scale bright condensations, most of them located inside the shells (N62B, N186D) not associated with stars, of other condensations associated with early-type stars. These condensations seem to have different origins. A more representative ensemble is required in order to elucidate the mechanisms of formation of the condensations.

b. For the SNRs (N186D and N120):

The velocity components of the SNR are contaminated by a bright component due to superposed HII regions, in agreement with the results of Chu and Kennicutt (1988).

— A careful study of the stellar content of each nebula is required. The existing stellar catalogues do not list all early type stars interior to the bubbles. High reddening affects many of these stars.

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