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LARGE AND SMALL BUBBLES IN THE MESSIER 82 STARBURST

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RESUMEN

Se han identificado por lo menos 50 remanentes de supernova (las burbujas pequeñas) en la galaxia con brote de formación estelar M 82, y se han utilizado estudios de radiosíntesis con resolución lineal menor a un parsec para medir la distribución, luminosidad, tamaños y, en algunos casos, velocidades de expansión de estos remanentes. Se utilizan los remanentes para estimar la tasa de supernovas y por lo tanto una medición independiente de la tasa de formación estelar en el brote de formación estelar.

A una escala más grande, recientemente descubrimos cáscaras de hidrógeno neutro (las burbujas grandes) en absorción contra el radiocontinuo difuso del brote de formación estelar. Las cáscaras tienen radios de entre 30 y 60 pc y energías tan altas como 2×10^{52} erg, y probablemente se forman como consecuencia de las cáscaras empujadas por vientos de regiones con una alta tasa de formación estelar.

ABSTRACT

At least 50 supernova remnants (the small bubbles) have been identified in the M 82 starburst and radio synthesis studies with sub-parsec linear resolution have been used to measure the distribution, luminosity, sizes and, in some cases, expansion velocities of these remnants. The remnants are used to estimate the supernova rate and hence an independent measure of the star-formation rate in the starburst.

On a larger scale we have recently discovered neutral hydrogen shells (the large bubbles) in absorption against the diffuse radio continuum from the starburst. The shells have radii between 30 and 60 pc and energies as high as 2×10^{52} erg and most likely arise as consequence of wind-driven shells from regions of high star formation.

Key Words: **GALAXIES: INDIVIDUAL (M 82) — GALAXIES: ISM — GALAXIES: STARBURST — SUPERNOVA REMNANTS**

1. INTRODUCTION

Strong, extended 60 μm emission from the central regions of late-type galaxies is usually assumed to indicate a high star-formation rate, which cannot be sustained for the lifetime of the galaxy (e.g., Rieke et al. 1980). In view of its inferred relatively short lifetime, this phenomenon is usually known as a starburst.

The best studied example of a starburst is the central kiloparsec of the nearby irregular galaxy M 82. Over 50 compact radio sources are associated with the central starburst (Figure 1) and our MERLIN observations (Muxlow et al. 1994) showed the sources to have sizes ranging from 0.3 to 4 pc with many having shell or partial shell structures. These structures and sizes, along with the non-thermal spectral index and lack of rapid variability, confirmed the identity of many of the sources as supernova remnants (SNR).

These SNR in M 82 and other starbursts are proving an increasingly valuable tool in understanding the physics of the star-formation process. Assuming these SNR are produced by young massive stars, with ages of order 10^6 years, the SNR trace the recent star-formation history of the galaxy. Furthermore, from the supernova rate it is possible to estimate the formation rate of massive stars, which can be used, assuming an initial mass function, to estimate the total star-formation rate.

The starburst clearly will have a strong effect on the interstellar medium (ISM) of the host galaxy, not only through photoionization, but also strong stellar winds. We have recently discovered shells of atomic hydrogen in M 82 (Wills, Pedlar, & Muxlow 2002) which appear to be wind driven, created by regions of high star formation. Although shells of atomic hydrogen (H I) were noted in our Galaxy in the 1970s (e.g., Heiles 1979, 1984), and a number of nearby galaxies show similar structures, we believe our observations show the first evidence of such shells in a starburst galaxy.

2. STUDIES OF SUPERNOVA REMNANTS

The study of radio SNR in starburst galaxies provides unique information on their properties and evo-

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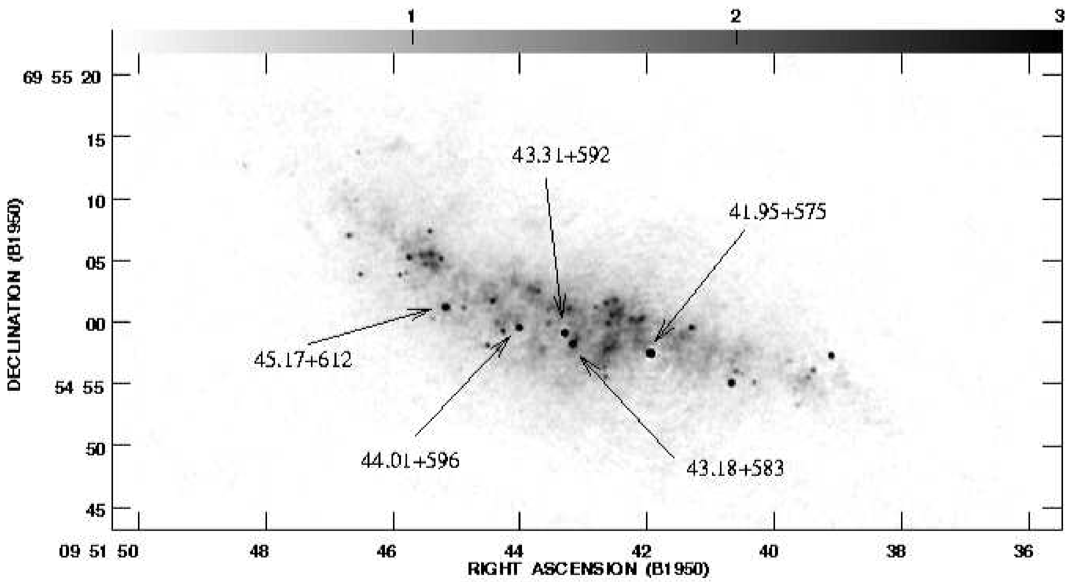

Fig. 1. 20 cm image of M 82 produced from combined MERLIN and VLA observations, showing the compact sources observed with VLBI.

lution. The remnants in a given starburst are essentially at the same distance and have been observed with identical angular/linear resolution and sensitivity (for example, as the starburst in M 82 has a size of < 1 kpc, then assuming a distance of 3200 kpc, the differences in relative distance for the sample of remnants is less than 0.03%!). It seems likely (Muxlow et al. 1994) that the remnants in M 82 have ages ranging from 30 to ~ 1000 years and hence observations of remnants in starbursts enables their properties to be parameterized over this age range.

Muxlow et al. (1994) plot the the radio luminosity of the components in M 82 against the measured sizes. It can be seen that most of the M 82 remnants are more luminous and more compact than their counterparts in the Large Magellanic Cloud (LMC) and our Galaxy. One question which needed to be addressed is whether the size of the remnants is a function of age, or whether the sizes are determined by the ambient density (e.g., Chevalier & Fransson 2001).

One method of distinguishing between these possibilities is to measure the expansion velocities of the remnants directly. To this end EVN measurements were carried out at two epochs (Figure 2) and an expansion velocity of one of the brighter remnants measured to be $\sim 10,000\,\mathrm{km\,s^{-1}}$ (Pedlar et al. 1999). If the remnant is in free expansion this implies an age of ~ 35 years, or shorter if significant deceleration has occurred. Recent Global VLBI measurements (McDonald et al. 2001) of these remnants have angular

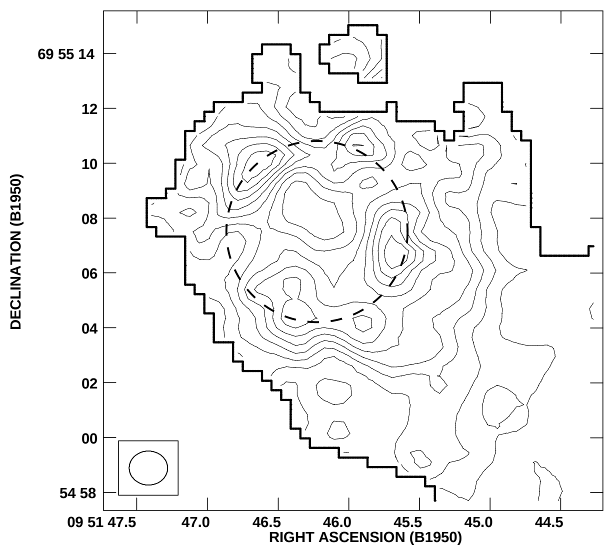

Fig. 2. European VLBI network 20 cm radio images of a shell supernova remnant in M 82 taken at two epochs separated by approximately 11 years. The expansion of the remnant implies an velocity of $9500\,\mathrm{km\,s^{-1}}$ (from Pedlar et al. 1999).

resolutions of a few milliarcseconds corresponding to ~ 0.06 pc. Given that 43.31+592 must have originated before it appeared on the early images in 1972 (Kronberg & Wilkinson 1975), it is already possible to rule out Sedov expansion suggesting that this remnant is still expanding close to free expansion.

It therefore appears that the size of at least some of the remnants give an estimate of their age,

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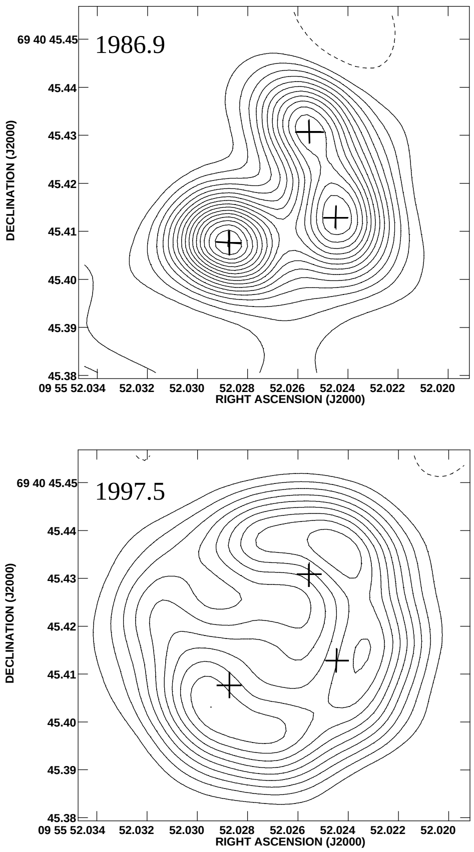

Fig. 3. A contour map of the H I optical depth in the vicinity of Shell 1 (from Wills et al. 2002).

and hence assuming a common expansion velocity of $10,000\,\mathrm{km\,s^{-1}}$, or simply assuming all the remnants more compact than Cas A are less than 330 years old, gives a supernova rate of $\sim 0.07\,\mathrm{yr}^{-1}$. This can be used to calculate a star-formation rate ($\geq 5\,M_{\odot}$) of $\sim 1.8\,M_{\odot}\,\mathrm{yr}^{-1}$. This is consistent with the ($\geq 5\,M_{\odot}$) star-formation rates derived from the FIR emission, non-thermal radio continuum and the thermal continuum all of which give values close to $2\,M_{\odot}\,\mathrm{yr}^{-1}$ (Pedlar 2001).

3. STUDIES OF NEUTRAL HYDROGEN SHELLS

The neutral hydrogen absorption against the non-thermal continuum has been extensively studied using MERLIN (Wills, Pedlar, & Muxlow 1998) and the VLA (Wills et al. 2000). The first paper dealt with absorption against individual remnants on parsec scales, and the second was largely concerned with the overall dynamics of the neutral gas over the central kiloparsec and its relation to a possible barred potential. On scales of 50 to 100 pc, however, it was possible to see shell/bubble-like structures in the neutral gas in absorption against the diffuse radio emission associated with the starburst. An example of one of these shells is shown in Figure 3 and a detailed report of this work is given by Wills et al. (2002).

At least four distinct shells can be identified and all show signs of line splitting and in shells 1 to 3 we see evidence of expansion from the inspection of individual channel maps. In view of this, we constructed position-velocity diagrams across the centers of the shells from a slice of one pixel in width across the declination axis. From these we have deduced approximate values for the expansion velocities. We also find other, less clear regions of line splitting across the starburst region but none of these can be unambiguously associated with shell-like structures.

Independent evidence for the existence of Shell 3 is also seen in the CO observations of Matsushita et al. (2000). This CO shell shows good agreement both in size and centroid position with our H I Shell 3.

4. A COMPARISON WITH H I SHELLS IN OTHER GALAXIES

Heiles (1979) initially identified 63 shells in our own Galaxy and studies of nearby external galaxies such as M 31, the LMC and Small Magellanic Cloud (SMC), have typically shown more than one hundred similar features. Emission studies of H I shells have been extended to galaxies at similar distances to M 82 and as many as ~ 50 shells have been detected in dwarf galaxies such as Holmberg II (Puche et al. 1992), IC 2574 and DDO 47 (Walter 1999). However, not all galaxies out to the M 82 distance appear to show these features and in fact, in NGC 3077 (in the M 81 group) no expanding shell-like features are visible (Walter 1999). Walter (1999) has tentatively attributed this to the strong tidal forces acting on NGC 3077 due to interactions with M 81 and M 82.

As M 82 is also strongly interacting with M81 (Yun, Ho, & Yo 1993), we might expect its interstellar medium to suffer similar disruption to that of NGC 3077 and therefore also be devoid of shell-like structures. However, given our detection of at least 4 H I shells in M 82, an alternative mechanism possibly needs to be considered to explain the lack of shells in NGC 3077. Note that in comparing M 82 and NGC 3077 there is an order of magnitude difference in the linear resolution of the respective observations and hence small shells in NGC 3077 may have escaped detection.

Although we have discovered a relatively small number of shells in M 82, it is important to emphasise that strong selection effects are present in our observations, which have hindered the unambiguous detection of large numbers of shells. Unlike the H I emission studies in the galaxies discussed above, our observations have been made in H I *absorption* and hence can be only made where there is a strong continuum background. In the case of M 82 this background is mostly non-thermal radio emission generated by the starburst. This limits our sampling area to the central 700 pc×150 pc of M 82 whereas the total extent of H I gas extends over $\sim$ 10 kpc (Yun et al. 1993). As a result of our small sampling area, our detection of 4 clear shells in M 82 actually represents a higher density of shells per unit area compared with the above galaxies. For example, if we compare our results with Holmberg II (Puche et al. 1992), IC 2574 (Walter 1999), and the LMC (Kim et al. 1999), then we can estimate that the number of shells per square kiloparsec are 0.5, 0.2, and 2.5 respectively. In M 82, since we have detected 4 shells in the central 700 pc×150 pc, then this gives a crude estimate of 12 shells per kpc^2. We note that a further selection effect is that we are only sensitive to shells on the near side of the central continuum and therefore our estimate represents a lower limit. Furthermore, in view of the small sampling area we are insensitive to shells larger than $\sim$ 500 pc.

Given that the linear resolution of the H I emission observations of the LMC (Kim et al. 1999) is the same as our M 82 absorption study, we can directly compare the parameters of the LMC shells with our results. Although the sizes of the M 82 shells lie in the lower end ($\sim$ 30 to 50 pc radius) of the LMC size distribution, the M 82 shells have higher expansion velocities ($\sim$ 30 km s^{-1}) than their counterparts with comparable sizes in the LMC ($\sim$ 15 km s^{-1}; see, for example, Figure 8 of Kim et al. 1999). In fact, the M 82 expansion velocities are more similar to the expansion velocities of the "supergiant" shells ($\gtrsim$ 200 pc radius) reported by Kim et al. (1999). Similarly, the kinetic energies derived for the M 82 shells (10^{51} to 10^{52} erg) are comparable to the energies of the LMC supergiant shells, and typically $\sim$ 20 times larger than similar-sized LMC counterparts.

The ages of the more compact LMC shells (< 100 pc radius) are derived by Kim et al. (1999), using the standard theory of wind-driven bubbles (Weaver et al. 1977), to be typically 2 to 6 Myr. This assumes that the shells have not yet broken out of the H I disk and, unlike the "supergiant" shells, have not reached the momentum-conserving phase of their expansion. If we estimate the ages of the M 82 shells using the same assumptions, then we derive ages of $\sim$ 1 Myr. If these ages are correct then the average

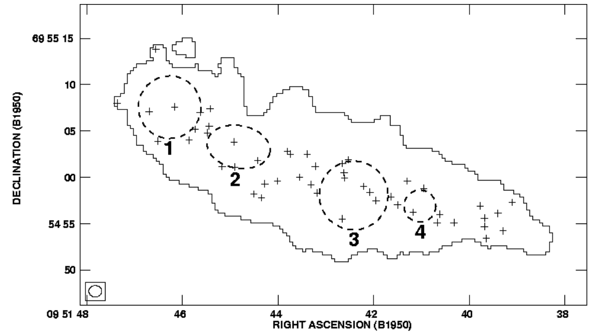

Fig. 4. The positions of the H I shells (dashed rings) in M 82 with the compact radio sources—mostly SNR—shown as crosses.

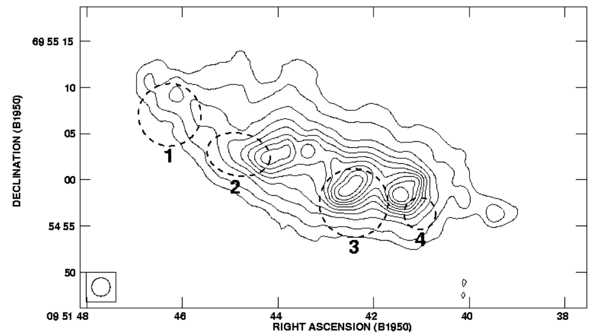

Fig. 5. The positions of the H I shells shown superimposed on the ionized gas distribution—derived from the [Ne II] measurements of Achtermann & Lacy (1995).

rate of energy input to the M 82 shells, via mechanisms such as stellar winds, must exceed the rate of energy input to the compact LMC shells by at least an order of magnitude. This difference could be a consequence of the higher star-formation rate in the M 82 starburst. There appears to be more than an order of magnitude difference in the M 82 and LMC star-formation rates as indicated by their respective supernova rates of 1 every 20 years for M 82 (Muxlow et al. 1994) and 1 every 250 years for the LMC (Meaburn 1991).

5. ASSOCIATION OF THE M 82 SHELLS WITH OTHER FEATURES

It is still unclear how H I shells are formed. Heiles (1979) suggested, from energy considerations, that they could be the consequence of multiple supernovae, whereas more recent work, based on observations of the LMC (Kim et al. 1999), indicates that H I shells may be formed via strong stellar winds from OB associations.

In order to investigate the association of the M 82 shells with supernovae, we have plotted the positions of the compact sources and the H I shells in Figure 4.

Of the 49 compact sources identified in M 82, the majority are supernova remnants (Muxlow et al. 1994), although some of the weaker sources may be compact H II regions. From this figure, we observe that the four H I shells lie along the major axis of the starburst in the same region as the compact sources, although note that this may be a selection effect since good absorption measurements are only possible against the continuum associated with the starburst. We also find that the compact sources tend to be neither clustered towards the centers of the shells nor located around their periphery. Note that the strongest compact source (41.95+57.5) is located close to the edge of Shell 3.

The positions of the H I shells with respect to the ionized gas is shown in Figure 5. The ionized gas distribution has been derived from [Ne II] emission-line observations presented by Achtermann & Lacy (1995). In this case we find that, although the shells are not centered on the peaks of ionized gas, Shells 1, 2, and 3 all contain local maxima in the ionized gas distribution and Shell 4 is close to the westernmost ionized gas peak (about 41.3+59). Shells 3 and 4 also appear to be associated with the 100 pc "hole" reported at 408 MHz (Wills et al. 1998) which they ascribe to free-free absorption by ionized gas.

If the ages of the H I shells are $\sim 10^6$ yr then it is not surprising that we do not observe an association between these shells and the compact sources. This is because many of these compact sources have been identified as supernova remnants which presumably represent regions of star formation typically 10^7 yr old (assuming this is a typical lifetime for a Type II supernova progenitor). However, if we assume that the current regions of star formation are delineated by the ionized gas distribution (Fig. 5), we would expect a close correspondence between the ionized gas and the location of the H I shells. In fact, we observe a displacement between the shells and the ionized gas maxima of typically 60 pc ($4''$—see above), which could be interpreted as a change in position of the star-formation regions during the shell expansion time (~ 1 Myr). In all four cases we observe that the direction of the displacement tends to be inwards, which could imply that the star-formation regions are moving inwards at 30 to 60 $\mathrm{km\,s^{-1}}$.

The possible association of the M 82 shells with the ionized gas distribution is consistent with the association of stellar clusters and H II regions with H I shells observed in the LMC (Kim et al. 1999). It is interesting to note that in the LMC, Kim et al. (1999) found that the more rapidly expanding shells are more likely to contain H II regions and OB associations. The fact that the M 82 shells are expanding much more rapidly than the LMC shells of similar size is consistent with this trend. Unfortunately, the small number of shells that we observe in M 82 all appear to be associated with regions of ionized gas and hence we cannot investigate the parameters of M 82 shells that do not contain H II regions.

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