PROCEEDINGS OF SCIENCE

Long term VLBI imaging and monitoring of the SNR in M82

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We present results from 20 years of global VLBI imaging of the supernova remnants in Messier 82. These observations, along with deep MERLIN 5 GHz observations, have traced the structural evolution of the most compact radio supernova remnants, measuring their source sizes, structures and expansion velocities. Additionally these observations constrain the rate at which these expanding shells are decelerating due to their interaction with the surrounding ISM.

The 9th European VLBI Network Symposium on
The role of VLBI in the Golden Age for Radio Astronomy and EVN Users Meeting
Bologna, Italy
September 23-26, 2

[1] Speaker

 http://pos.sissa.it

PoS(IX EVN Symposium)065

1. Introduction

Messier 82 is one of the closest, and consequently best studied, starburst galaxies. With a moderate star-formation rate of ~2 $M_{\odot} yr^{-1}$, implying a supernova rate of ~0.1 yr^{-1} [1, 2] it is no surprise that a large number of long-lived radio supernova remnants (SNR) are observed in the centre of M82. For the last two decades global Very Long Baseline Interferometry (VLBI) has been used to image the milliarcsecond radio structures of the brightest and most compact of these radio sources. To-date these VLBI studies [2, 3, 4, 5, 6, 7, 8] have concentrated on a few of the most compact of the >50 radio sources in M82 [9 , 10, 11, 12]. This has primarily been due limited sensitivity of VLBI observations which are unable to image the fainter and more extended emission that makes up the majority of the remnants in M82.

Increasingly VLBI observations have become more sensitive by exploiting larger bandwidths. However, only by making simultaneous dedicated observations using VLBI in combination with shorter-spacing interferometers, such as MERLIN, has it now become possible to resolve and image many tens of SNR in M82 (e.g. [7, 8, 14]). In these proceedings we will provide an overview the last 20 years of VLBI observations of the most compact sources in M82 which began in the mid-1980s and discuss the structure and evolution of these young remnants.

2. 20 years of VLBI observations on M82

In total there are greater than 50 compact radio sources observed with MERLIN and VLBI in M82 [9, 11, 13, 14]. Long term monitoring of the flux density of these sources [15, 16] has shown that the vast majority are not variable and hence likely to be a combination of compact HII regions and radio SNR. Almost all of these sources are well-resolved by high resolution 5 GHz observations using MERLIN [9, 13] with most showing partial shell-like structures typical of SNR expanding into the ISM. Using this structural information along with information on their radio spectral energy distributions [10, 11, 12] these sources have been classified; with ~2/3 consistent with being SNR and the remainder being HII regions. A small number of these sources are more compact, remaining only partially resolved by these connected-interferometer observations. These sources have been the target of early VLBI observations in the mid-1980s [3, 4, 5], with these and subsequent VLBI observations mainly focused upon the two brightest and most compact radio sources, 41.95+57.5 and 43.31+59.2.

Milliarcsecond angular resolutions VLBI observations resolve away the majority of the sources in M82 with only the few most compact sources being detected. The four most compact, bright sources are 44.01+59.6, 45.17+61.2, 41.95+57.5 and 43.31+59.2; these are only partially resolved by MERLIN. The results of long term VLBI monitoring of these four sources is discussed in the following sections.

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3. Results

3.1 The compact radio source 41.95+57.5 and its nature

The source 41.95+57.5 is the most compact radio source in M82 and has tentatively been identified as a supernova remnant although this classification remains uncertain. This source is only marginally resolvable in MERLIN and VLA observations, but because of its high flux density and compact nature it has become a repeated target for VLBI observations. Some of the earliest VLBI observations of this source were made in the mid-1980s by Bartel et al [3], Trotman [4] and Pedlar et al [5]. These, and subsequent VLBI observations up to and including the most recent in 2005 [2, 6] show 41.95+57.5 to have a bipolar radio structure unlike typical SNR which normally display a ring or partial ring-like structure (Fig. 1). Long term multi-epoch VLBI observations of this source have shown that there is some evidence for a slow increase in the angular separation of the two primary hot-spots in 41.95+57.5. The measurement of this separation has proved difficult due to the structural and flux density evolution of individual components. However, Gaussian fits to the components in the first four of these epochs are consistent with an expansion speed of ~2000kms^{-1} [2, 4, 6]. Assuming this source is still in free-expansion this implies an age of around 100 years. In the most recent VLBI (2005 epoch) the structural and flux density evolution of these components has meant that little or no expansion is discernable and potentially a third, central component may be becoming visible.

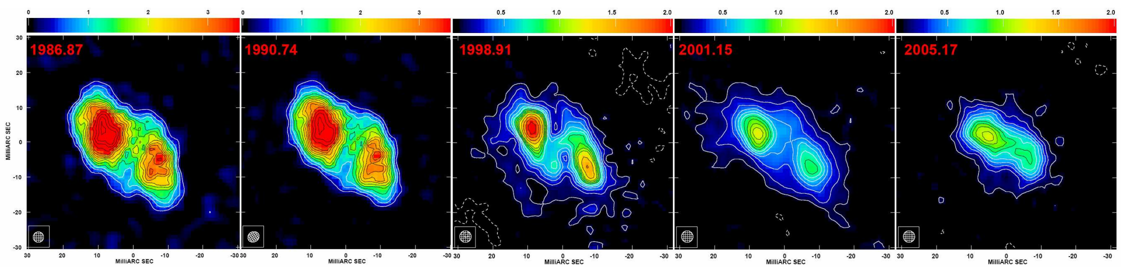

Figure 1: The structural evolution of the compact radio source 41.95+57.5 from 1986 through to 2005. The figure shows 1.6 GHz global VLBI images of 5 epochs (1986.87, 1990.74, 1998.91, 2001.15 and 2005.17). Each image has been convolved with a matching circular 3.3 mas beam. The total flux density of 41.95+57.5 is decreasing by ~8.8% per year. In the images presented the first two epochs are shown with an identical false colour scale. Equally the final three epochs are shown with matching colour scale.

Equally unusually for a SNR the total flux density of 41.95+57.5 is evolving in a significant manner. Since the initial measurements in the 1970s the flux density of 41.95+57.5 has been shown to be decreasing at a constant rate of ~8.8% per year [11, 15, 16 17]. Extrapolating this well-charted flux density decrease back to the projected age of the source (~100 years old) would imply a total flux density at outburst of ~100Jy. The combination of this large and consistent fading, and the observed milliarcsecond radio structure, along with circumstantial evidence from the ISM surrounding 41.95+57.5 has lead to considerable discussion as to the true nature of this unusual source. Suggestions include the possibility that it is a nearby example of a miss-aligned, gamma-ray burst radio afterglow [17]. However it remains feasible that 41.9+57.5 is a powerful SNR with characteristics more similar to SN1986J in NGC891 [18, 19] than other SNR in M82. SN1986J also displays a distorted radio structure and in recent times SN1986J is now showing evidence of a new central component emerging initially at high frequencies which is thought to possibly be associated with the pulsar-wind nebular. Continued VLBI observations at a variety of frequencies will be required to determine the true nature of 41.95+57.5.

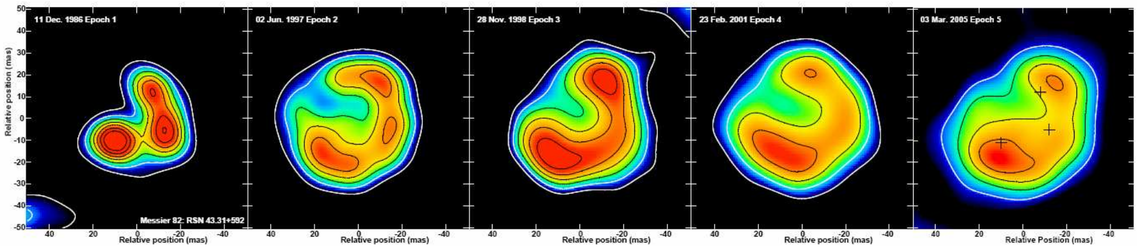

Figure 2: 1.6 GHz VLBI images of 43.31+59.2 from 5 epochs (Dec 1986, Jun 1997, Nov 1998, Feb 2001 and Mar 2005). Each of these images has been convolved with a circular 15 mas beam. All images are plotted with a matching flux density false-colour scale ranging from 0.1 to 2.2 mJy beam^{-1}. The positions marked in the final image represent the Gaussian fitted positions of the primary components observed in 1986 [2, 5, 6, 8].

3.2 The SNR 43.31+59.2

The most ring-like of the bright, compact SNR is M82 is 43.31+59.2 (see Fig. 2). A comparison between the 1986 and 1997 EVN images of 43.31+59.2 [5] showed an obvious increase in size consistent with an expansion velocity of ~10,000kms^{-1}. The continuing expansion of this source is evident in all later epochs with expansion velocities of 9,000—11,000kms^{-1} being measured (see Fig. 3). This VLBI measured expansion speed is consistent with measurements made using MERLIN over a 10 year baseline between 1992 and 2002 which

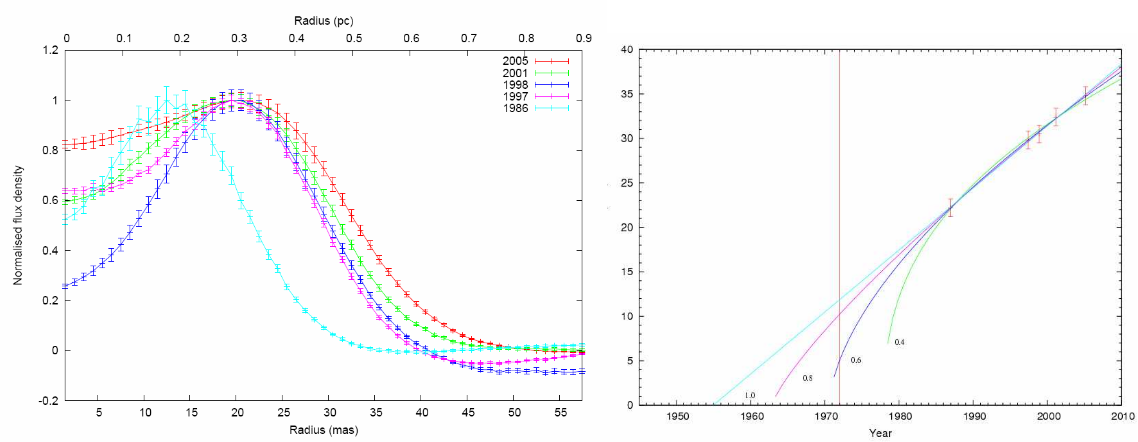

Figure 3: (Left) Radial flux density profile of the SNR 43.31+59.2 for each of the 5 epochs derived from the 15 mas resolution VLBI images. Significant radial expansion is seen between each epoch. **(Right)** A plot of the measured shell radius against date with fitted expansion models superposed for fixed deceleration parameters 1.0, 0.8, 0.6 and 0.4. Note the red vertical line represents the first radio detection of this source in 1972 [20], placing a minimum age limit on this source and eliminating models with deceleration parameters >~0.6.

derives an expansion velocity of 8,800±600 kms^{-1} [13]. Current expansion measurements are consistent with this young remnant still being free expansion, although tentative evidence for deceleration is now being seen in the most recent epochs [2, 8].

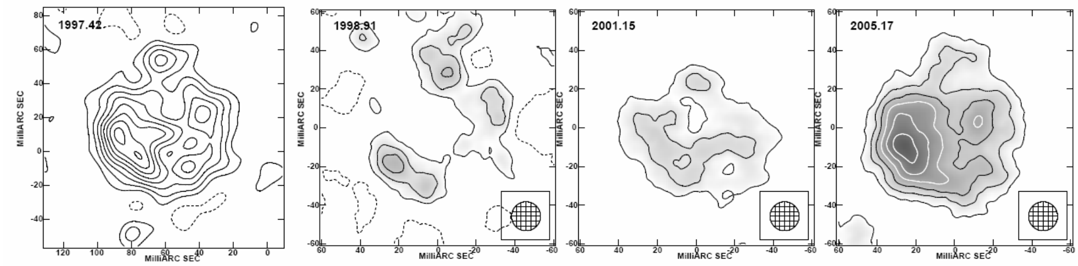

Figure 4: Four epochs of 1.6 GHz global VLBI images of SNR 44.01+59.6 between 1997 and 2006.

3.3 Supernova remnants 44.01+59.6 and 45.17+61.2

In addition to the two brightest and most compact objects in M82, with sensitive VLBI observations it is also possible to image and monitor the morphological evolution of two further sources 44.01+59.6 and 45.17+61.2 [5, 6, 8]. Both of these two sources have been identified by there radio spectra as supernova remnants [10, 11, 12] and in recent long term monitoring at 5 GHz with MERLIN have been shown to be expanding at 2700±400kms^{-1} and ~6000kms^{-1} for 44.01+59.6 and 45.17+61.2 respectively [13]. At VLBI resolution 44.01+59.6 shows a partial ring-like structure, with a tentative expansion measurable (see Fig. 4). However, the image fidelity of the VLBI observations so far made, combined with the relatively low surface brightness of this source have made definitive determinations of the expansion of this source with VLBI difficult. The remnant 45.17+61.2 at milliarcsecond resolution displays a complex structure with no clear ring like structure (see Fig. 5) typical of compact radio supernovae such as 43.31+59.2. Multiple future epochs of higher sensitivity VLBI imaging, utilising additional short spacing data from combined MERLIN observations will be required to full characterise the expansion of both of these sources.

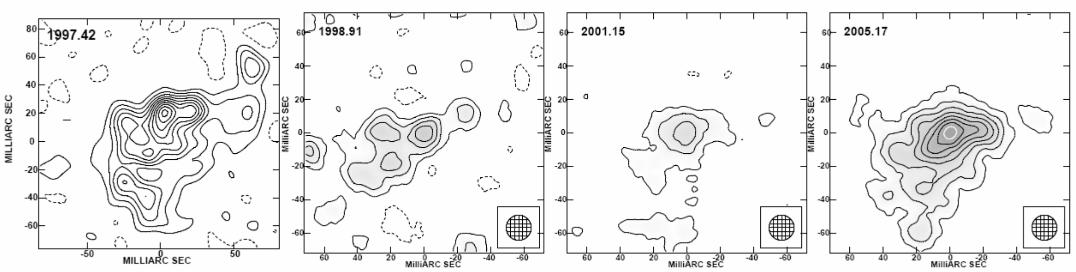

Figure 5: Four epochs of 1.6 GHz global VLBI observations of SNR 45.17+61.2 between 1997 and 2005.

3.4 Conclusions and the future

VLBI observations of M82 over the last two decades have detected and characterised the morphological evolution of several of the most compact radio sources in the centre of this starburst galaxy. In particular the two most compact sources (41.95+57.2 and 43.31+59.2) have been studied in detail. In both of these sources VLBI observations have measured their rates of expansion, and in the case of 43.31+59.2 observations over the next few years will be able to measure the rate of deceleration as the remnant shock wave interacts with the surround ISM. VLBI observations of the most compact source, 41.95+57.2, have shown that morphologically this source is very atypical for a SNR. This source's bi-polar structure, along with its flux density evolution and environmental situation has lead to much ongoing speculation as to its true nature, including the possibility that it is a remnant from a ~100 year old GRB.

In addition to these two brightest and most compact radio sources several other fainter SNR are now observable in M82 using high resolution VLBI techniques. However the reliable determination of their structure over many years remains difficult.

The most recent set of VLBI observations made in 2005 has been made in combination with the MERLIN array. The combination of these high resolution arrays has resulted in the highest quality VLBI resolution observations of M82 to date. These results will be presented in full in Fenech et al 2009 [8] and allow images to be made of, and the determination of sizes for, many tens of individual SNR at VLBI resolutions for the first time. These observations combined with future planned epochs will hence provide a statistical analysis of the expansion rates of remnants throughout the central starburst regions and a unique probe of the ISM around individual sources.

Acknowledgements

The European VLBI Network is a joint facility of European, Chinese, South African and other radio astronomy institutes. The VLBA is operated by the National Radio Astronomy Observatory, a facility of the National Science Foundation, operated under cooperative agreement by Associated Universities, Inc.

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