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VLBI Monitoring of the most compact sources in M82

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We present the results of the ongoing investigation of the compact radio sources within the central kpc of M82. The most recent global VLBI observations at 1.7 and 5 GHz, attaining an angular resolution of 4 mas and 1 mas respectively, have been used to image the unusual source 41.95+57.5. Previous global VLBI observations at 1.7 GHz from 2005 have also been combined with archival VLBI and EVN observations to monitor the expansion of the supernova remnant 43.31+59.2. We also discuss the combination of these global data with simultaneous MERLIN observations.

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1. Introduction

Radio studies of starburst galaxies can reveal populations of supernovae and supernova remnants (SNR) unobservable at other wavelengths because of the high levels of gas and dust associated with the intense star-formation. As a by-product of the star-formation process, these supernovae and SNR play an important role in the feedback of energy and material into the surrounding interstellar medium.

M82 is one of the closest examples of a starburst galaxy and as such provides a unique opportunity to study a population of young compact radio sources at essentially equivalent angular resolution and brightness sensitivity. In contrast, study of Galactic SNRs is hindered by inaccurate distance estimates and by the fact that the youngest known SNR are over 150 yrs old [1].

The central kpc of M82 is now known to contain approaching $\sim$100 discrete sources believed to be predominantly SNR and HII regions, with the exception of the new supernova SN2008iz [2, 3] and the new radio tranisent first detected in May 2009 [4, 5], which will not be discussed here. These SNR form a population of sources younger and brighter than their Galactic counterparts. As a consequence, since the first observations in the 1960/70s [6, 7], M82 has become well-studied at radio wavelengths, resolving all of the observed sources with either MERLIN and/or VLBI observations [8, 9, 10, 11, 12, 13].

2. Global VLBI observations

VLBI monitoring has been used to study the evolution of two of the most compact sources in M82 since 1986. These early measurements and subsequent observations from 1997 utilised the EVN at 1.7 GHz [10]. Further global VLBI observations were made at the same frequency in 1998, 2001 and 2005 [11, 12, 14] continuing a now well established monitoring campaign. These five epochs of global data have been used to image and monitor the expansion of a young rapidly evolving supernova remnant, 43.31+59.2 (see section 2.2). This was believed to be the youngest supernova remnant in M82 until the discovery of the new radio supernova, SN2008iz.

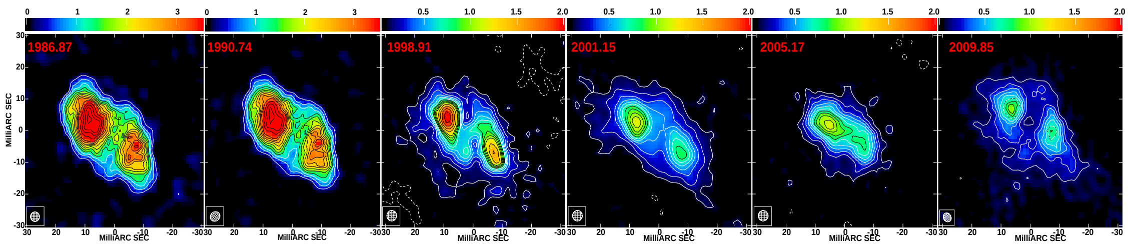


Figure 1: Contour and colour-scale images of 41.95+57.5 restored with a 3.3 mas circular beam. Contours are plotted at $-1,1,2,3,4,5,6,7,8,9,10\times$ 0.31 mJy beam^{-1} for the first two epochs and $\times$ 0.11 mJy beam^{-1} for the latter four. The colour-scale is linear ranging from 0 to 3.5 mJy beam^{-1} for the first two epochs and 2.0 mJy beam^{-1} for the remaining four epochs.

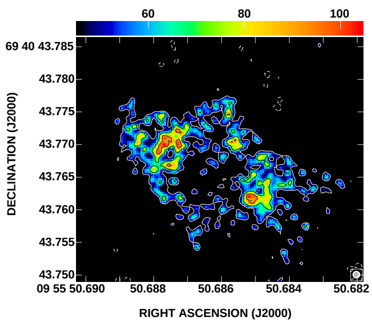
The global VLBI observations have also been used to observe the most compact source 41.95+57.5. The 15 mas beam of the EVN observations does not fully resolve this source and, as a result, only the global VLBI observations have been used to monitor its evolution on scales of a few mas, corresponding to ∼0.05 pc [12], (see section 2.1). However, archival global VLBI observations from 1987 and 1990 have now been combined with these later epochs [15, 16].

New 1.7 GHz global VLBI observations were performed in October 2009 using a sixteen element array. This incorporated six of the EVN antennas and all of the ten VLBA antennas to match the setup for previous experiments. Observations of the phase reference source J0958+65 were made by switching between this and M82. The sources 3C84 and J0927+39 were also observed and used in the fringe-fitting and bandpass calibration. MERLIN observations were performed simultaneously for combination with the global data as for the previous 2005 global VLBI observations. In addition simultaneous MERLIN and global VLBI observations were made at 5 GHz in November 2009 to provide higher resolution images.

2.1 41.95+57.5

Until the appearance of the new supernova SN2008iz, 41.95+57.5 was the most compact source within M82. Fig. 1 shows contour and colour-scale images of this source from all available global VLBI observations at 1.7 GHz and clearly shows a distinct bi-polar structure, atypical of the ring-like morphology expected of supernova remnants. Observations of this source at 2.3 GHz and 5 GHz showed a structure indicative of an elongated shell, hence its initial classification as a SNR [17, 15]. Further observations at 1.7 GHz using the EVN confirmed this elongated structure, sized 20×10 mas [10, 12].

41.95+57.5 is also unique in that it continues to display a decay in flux density at a rate of ∼8.5% per year. This decay has been evident from the first observations of M82 in the early 1960's. This source also appears to be undergoing signifcant structural evolution over the time-period of the monitoring programme, which can be seen both in the contour images (see Fig. 1 and Fig. 2) and the flux density slices taken across the major axis of the source, also shown in Fig. 2.



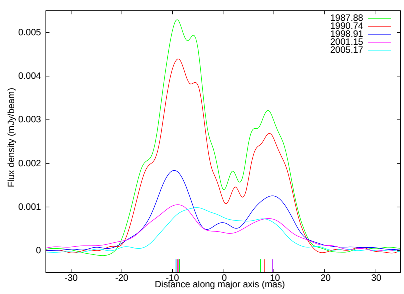


Figure 2: Left: Contour and colour-scale image of 41.95+57.5 restored with a 1 mas circular beam from the 2009 5 GHz global VLBI observations. Contours are plotted at $-1, 1, 1.5, 2..4.5, 5\times$ 45 μJy beam^{-1}. The colour-scale is linear ranging from 45 to 105 μJy beam^{-1}. Right: Flux density slices along the major axis from all of the global VLBI observations at 1.7 GHz.

The previous global VLBI observations of 41.95+57.5 have been used to estimate a relatively low expansion velocity between the bright knots of radio emission, of 1500 ± 400 km s^{-1}[12]. Assuming free-expansion this provides an upper-limit for the age of 41.95+57.5 of ∼ 100 yrs.

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Muxlow et al. 2005 [18] suggested that it could be an evolved gamma-ray burst (GRB) remnant, citing that the bi-polar structure could be explained by the oppositely directed jets associated with a GRB event.

There is however, continued speculation as to the true nature of this source. The unusual supernova SN1986J in NGC891 also showed characteristics atypical of the expected expanding-shell scenario, and similar to those of 41.95+57.5, with an elongated morphology and an observed relatively low expansion velocity of $\leq$1700km s^{-1}[19]. VLBI observations of SN1986J in 2004 revealed the emergence of a compact core believed to be a pulsar or an accreting black hole [20]. Higher resolution global VLBI observations were made in 2009 at 5 GHz to determine if 41.95+57.5 was showing a similar evolution. However, as can be seen in Fig. 2, there is not yet any obvious sign of a compact core developing.

2.2 43.31+59.2

43.31+59.2 is believed to be the youngest of the SNR within M82. In contrast to the unusual nature of 41.95+57.5, 43.31+59.2 shows a very well-defined shell structure, see Fig. 3. The VLBI monitoring programme has enabled the study of its evolution over a 19 year time-line, providing important information on the nature of such SNR and the environments they occupy. Previous investigations using VLBI observations (e.g. [10, 11, 12]) have shown 43.31+59.2 to be expanding at $\sim 10^4$ km s^{-1}. The more recent comparison of the 2005 global VLBI observations with previous epochs yields a slightly lower expansion velocity, 7600$\pm$1800km s^{-1}[14]. This could indicate that the expansion has begun to decelerate and a comparison of velocities determined from various epochs (shown in Fig. 4), shows tentative evidence for such a trend.

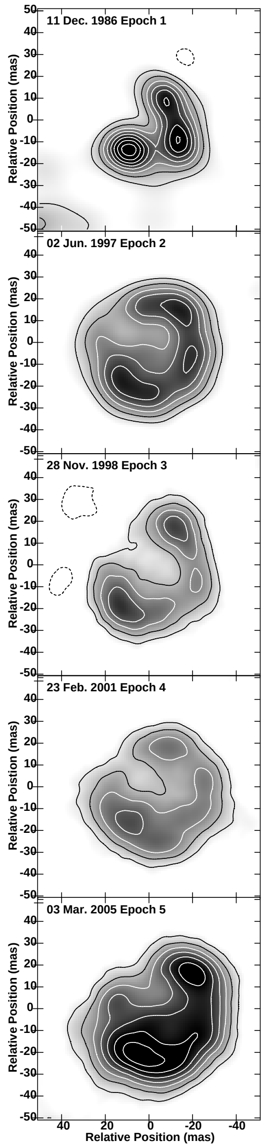

Figure 3: Contour and grey-scale images of the SNR 43.31+59.2 from each epoch of the VLBI observations. Contours are plotted at -1,1,2,3,4,5,6,7,8,9,10 $\times$ 0.35 mJy beam^{-1} and the grey-scale is linear ranging from 0.1-2.2 mJy beam^{-1} for the first three epochs and from 0.1-1.7 mJy beam^{-1} for the remaining two. Taken from Fenech et al. (2010) [14].

The evolution of a SNR can be parameterised as $D = kT^{\delta}$, where D is the size of the remnant and T is its age. δ represents the deceleration parameter and k is a constant [21, 11]. Fig. 4 shows the size measurements at 50% of the peak value, for each epoch with several fitted deceleration curves. These sizes are taken from 15 mas resolution images to enable comparison with the EVN-only epochs. It is unfortuantely not possible to distinguish at this stage whether this source is in fact decelerating, though inclusion of the most recent epoch of observations from 2009 may make any deviation from free-expansion more evident.

As the actual birth-date is unknown, a lower limit can be provided by taking the first detection of 43.31+59.2 in 1972. This can be used to constrain the deceleration parameter, providing a lower limit of 0.53±0.06 (for a full discussion see [14]).

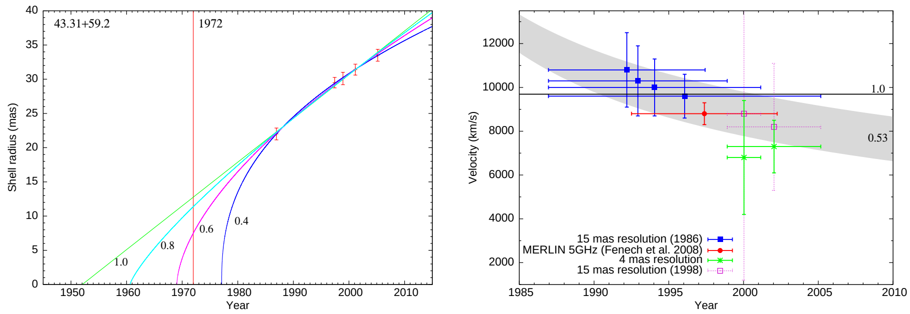

Figure 4: Left: Measured radius of 43.31+59.2 for the five epochs taken from [14]. Also plotted are four of the possible deceleration parameters fitted to the measurements. The vertical line shows the year of the first observation of 43.31+59.2. Right: The calculated expansion velocities using size comparison between various epochs. The horizontal error bar shows the start and end epoch dates used for the calculation.

3. MERLIN and global VLBI combination

In 2005, simultaneous observations of M82, using the seven element MERLIN array, were carried out with the global VLBI observations. These data were reduced using the MERLIN pipeline and utilised the same calibration sources as the global data. The combination of the MERLIN and global VLBI observations has provided the capability to image the sources with resolutions ranging from ∼3-130 mas. This enabled the first detailed study of the 36 detected sources at 1.7 GHz and the full results have been published in Fenech et al. 2010 [14]. Fig. 5 shows an example SNR (45.17+65.3) from the MERLIN only data and the combined data to illustrate the significant detail revealed through the combination of the observations. Also shown is the same source from previous MERLIN studies at 5 GHz. As an extension to this work, the most recent 2009 global VLBI observations were also performed in combination with MERLIN at both frequencies used. This will not only provide higher resolution imaging but will also enable the first opportunity to compare the whole of the observed population of SNR at different epochs to follow their evolution.

4. Summary

The 6th epoch of global VLBI observations of M82 have been used to image the unusual source 41.95+57.5. Alongside the previous archival global VLBI data, this has shown the structure to be continually evolving. In addition, the evolution of the SNR 43.31+59.2 has been studied through comparison of the previous VLBI observations of this source covering a 19 year timescale. Size measurements have been used to determine the expansion velocity of this source. It is hoped the most recent observations will begin to constrain the nature of the expansion of this source and determine if it is experiencing any deceleration.

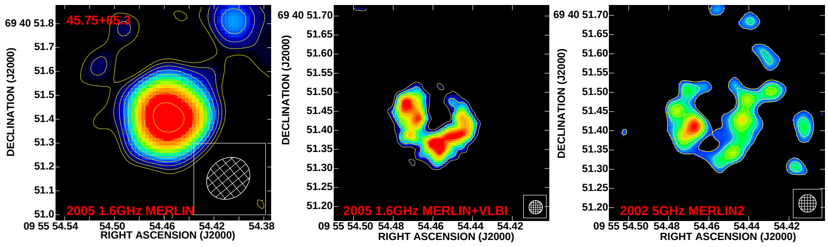

Figure 5: Left: Example SNR from the MERLIN-only observations (convolved with a 130 mas beam) and (middle) after combination of MERLIN and global VLBI (convolved with a 35 mas beam). Contours are plotted at $-1, 1, 1.414, 2, 2.828, 4, 5.656\times$ 120 and 88 μJy beam^{-1} respectively. The colour-scale is linear, ranging from 120-1500 and 88-300 μJy beam^{-1} respectively. Also plotted (right) is the same source from MERLIN 5 GHz observations [13], convolved with a 50 mas beam. Contours are plotted as equivalent multiples of 57 μJy beam^{-1} and the colour-scale range is 55-300 μJy beam^{-1}.

For the first time, a successful combination of simultaneous MERLIN and global VLBI observations at 1.7 GHz from 2005, has provided the opportunity to study the detail of the population of compact sources in M82 at a frequency other than 5 GHz [13].

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