Milliarcsecond monitoring of supernova remnants in M82

D. Fenech[a], T. W. B Muxlow[b], R. J. Beswick[b] and M. K. Argo[c]

[a] Astrophysics group, Cavendish laboratory, Univeristy of Cambridge, U.K. [b] Jodrell Bank Centre for Astrophysics, The University of Manchester, U.K, [c] Jeremiah Horrocks Institute, University of Central Lancashire, U.K.

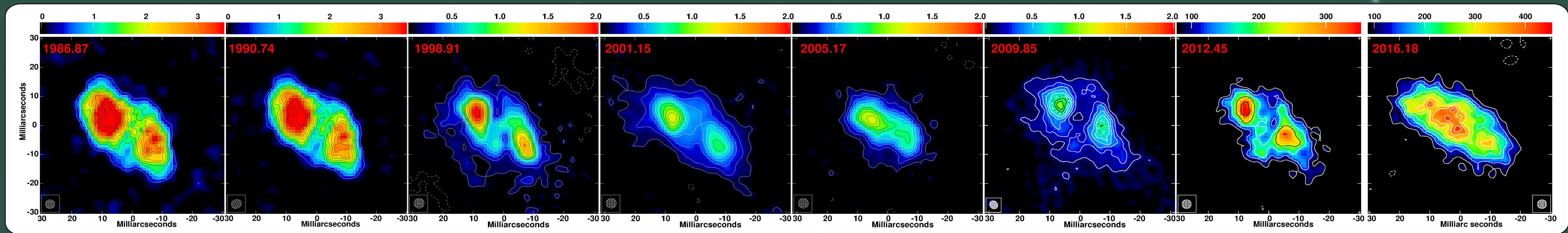
M82

M82 is considered a prototypical starburst galaxy, and as one of the closest (distance ~3.6Mpc) provides an ideal opportunity to study a star forming environment in detail. The first detailed radio studies of M82 revealed a number of compact sources in the central region first identified as either radio supernovae or supernova remnants (SNR; Hargrave 1974, MNRAS,168, 491; Unger et al. 1984, MNRAS,211,783). Their subsequent lack of variability confirmed their identity as SNR.

Further MERLIN (Multi Element Linked Interferometer Network), e-MERLIN and VLA (Very Large Array) observations have shown the central kiloparsec of M82 to contain at least 50-100 compact sources including supernovae, SNR and HII regions (Muxlow et al. 1994, MNRAS, 266, 455; Huang et al. 1994, 424, 114; Fenech et al. 2008, MNRAS, 391, 1384; Brunthaler et al. A&A, 593, 18).

High-resolution monitoring

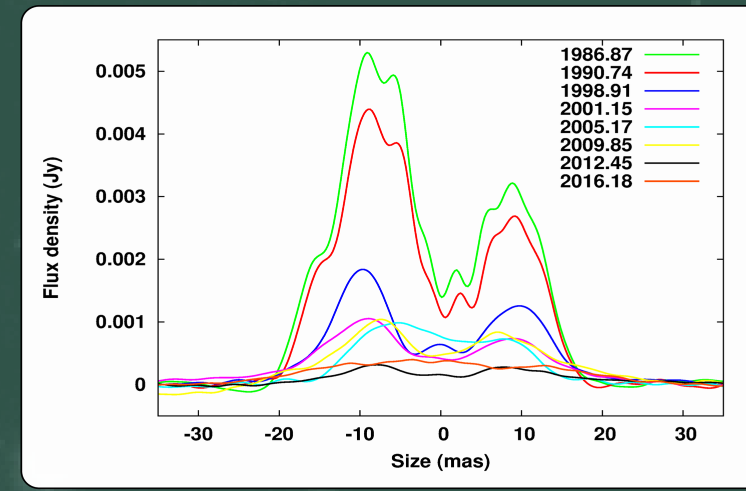
A continued high-resolution monitoring programme has been used to study the evolution of at least one of the most compact sources in M82 since 1986 (Bartel 1987, ApJ, 323, 505). These have been combined with subsequent observations from 1997 utilising the EVN at 1.7-GHz as well as more recent global VLBI observations made at the same frequency every 2-3 yrs from 1998 to 2016, continuing a well established campaign to image and monitor the expansion of the young rapidly evolving supernova remnant, 43.31+59.2 as well as the unusual bi-polar source 41.95+57.5 (Pedlar et al. 1999, MNRAS, 307, 761; McDonald et al. 2001, MNRAS, 322, 100; Beswick et al. 2006, MNRAS, 369, 1221, MNRAS; Fenech et al. 2010, MNRAS, 408, 607). The latter three epochs of this programme have also included observations at 5-GHz providing enhanced resolution at ~1-mas. The most recent of which were performed in Nov. 2015 and Feb. 2016 using 22 antennas (including 10 VLBA antennas) and provide the most high-fidelity, high-resolution images of the compact sources within M82.



Global VLBI 1.7-GHz 3-mas images of 41.95+57.5 at multiple epochs showing almost 30 years of evolution. Colour-scale is shown in mJy.

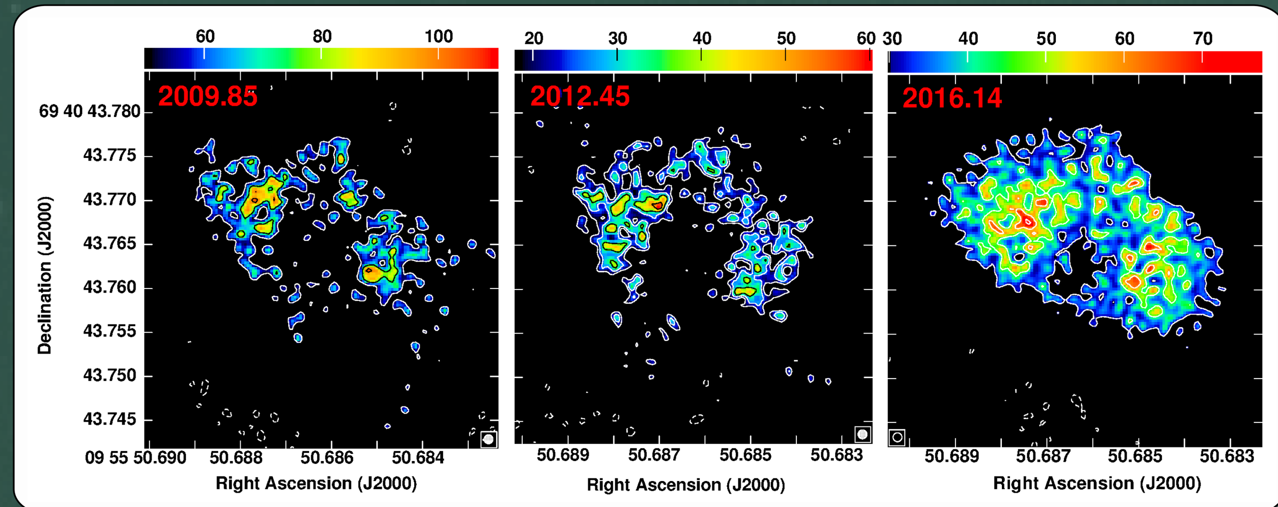
41.95+57.5

Until the appearance of the new supernova, SN2008iz and the transient source (43.78+59.3), 41.95+57.5 was the most compact source within M82. This source has been characterised by its distinct bi-polar structure, atypical of the ring-like morphology expected of SNR. Early observations of 41.95+57.5 at 2.3-GHz and 5-GHz showed a structure indicative of an elongated shell, hence its initial classification as a SNR. The global VLBI observations performed in 2009, 2012 and 2016 included both 1.7-GHz and 5-GHz data (see figures above and below respectively). The 5-GHz higher resolution images clearly show that there may in fact be more ring-like emission associated with this source, alongside the knots of radio emission usually observed as a more bi-polar structure. Preliminary analysis from the latest 5-GHz observations suggests a potential expansion velocity of this ring-like structure of ~1500 kms^{-1} (assuming a distance of 3.6 Mpc), in broad agreement with previous measurements from the 1.7-GHz knots of emission (Beswick et al. 2006, Fenech et al. 2010).



Slice profiles along the major axis of 41.95+57.5 from the 3-mas resolution 1.7-GHz observations.

41.95+57.5 is also unique in that it continues to display a decay in flux density. This decay, initially constant at a rate of ~8.5% per year has been observed since the earliest radio measurements of M82 in the early 1960's. More recent MERLIN observations have now shown this decay to have decreased to around 6.4% per year (Gendre et al. 2013, MNRAS, 431, 1107). The right figure shows slice profiles from each epoch at 1.7-GHz taken along the major axis of the source, defined as the line between the two radio peaks. This clearly shows the decay occurs across the whole source structure, though the preliminary analysis of the most recent observations is perhaps indiciative of a central brightening.

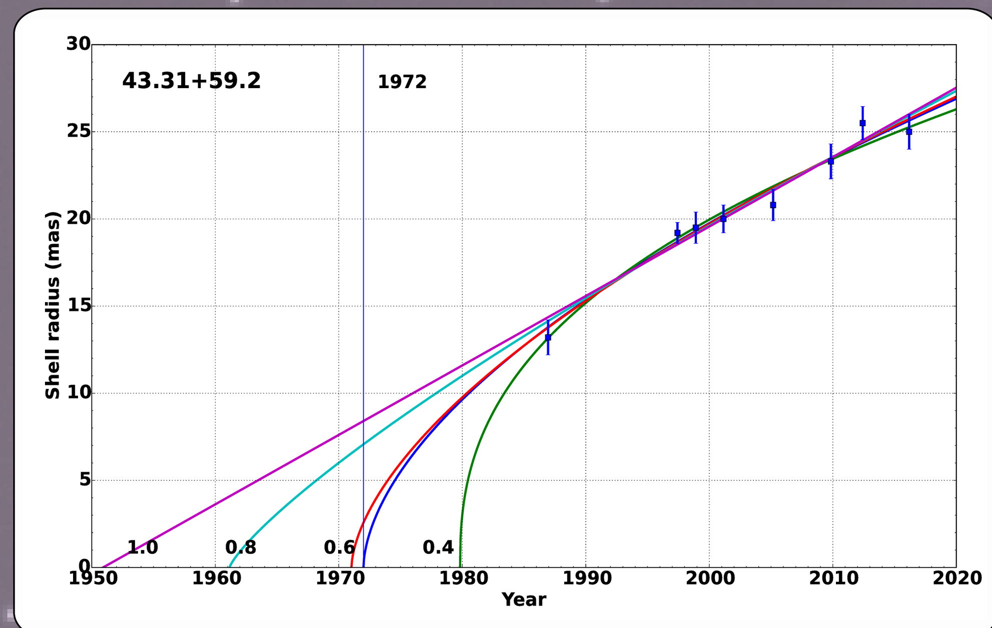


Left: Global VLBI images of 41.95+57.5 at 5-GHz with 1-mas resolution. Colour-scale is shown in mJy.

43.31+59.2 - a typical SNR

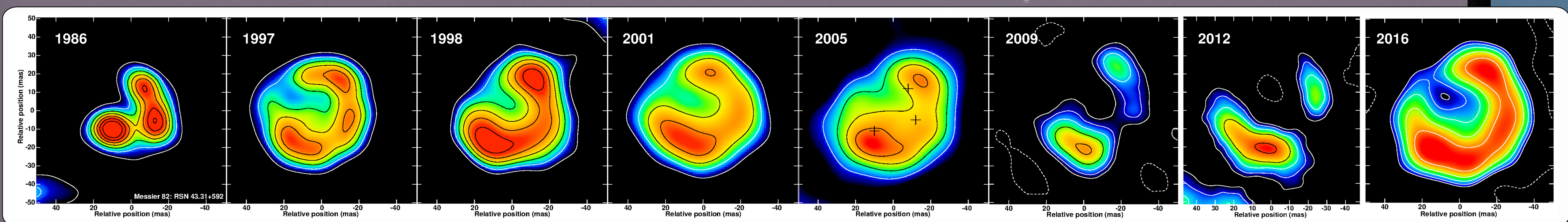
First observed in 1972, 43.31+59.2 shows a very well-defined shell structure (see Figure below), in contrast to the unusual nature of 41.95+57.5. This source, believed to be the youngest of the SNR within M82, appears to be undergoing a more typical evolution. Investigations using early VLBI observations have shown 43.31+59.2 to be expanding at ~10000 kms^{-1} (Pedlar et al. 1999). More recently, a comparison of the 2005 global VLBI observations with previous epochs suggested a slightly lower expansion velocity of 7600±1800 kms^{-1} (Fenech et al. 2010). This could indicate that the expansion has begun to decelerate and a comparison of velocities determined from various epochs shows tentative evidence for such a trend (see Fig. 8, Fenech et al. 2010). The evolution of a SNR can be parameterised as $D = kt^m$, where D is the size of the remnant (mas), t is the age of the remnant (yrs), m is the deceleration parameter and k is a constant. Incorporating the preliminary results from the later epochs of global VLBI observations into this analysis provides a maximum deceleration parameter of 0.57±0.05, suggesting this remnant has yet to reach the Sedov phase of evolution characterised by m~0.45. The left figure shows radius vs. time with several fitted deceleration parameters including the current best fit.

Supernova remnant evolution can also be used to probe the properties of the interstellar medium surrounding the remnant. In particular it is possible to determine the density of the interacting medium. $r_s \cong 4.1\ (M_{ej} / n_{ISM})^{1/3}$ describes the expected relationship for the size of the remnant (r_s in pc), the mass ejected in the supernova explosion (M_{ej} in units of $10M_\odot$) and the density of the surrounding medium (cm^{-3}; Parra et al. 2007, ApJ, 659, 314) at the peak of radio emission when the mass of material swept up in the expansion is equivalent to the ejected mass i.e. at the initiation of the Sedov phase. assuming a typical $5M_\odot$ ejecta, provides an upper limit to the ISM density of ~400 cm^{-3} surrounding 43.31+59.2.



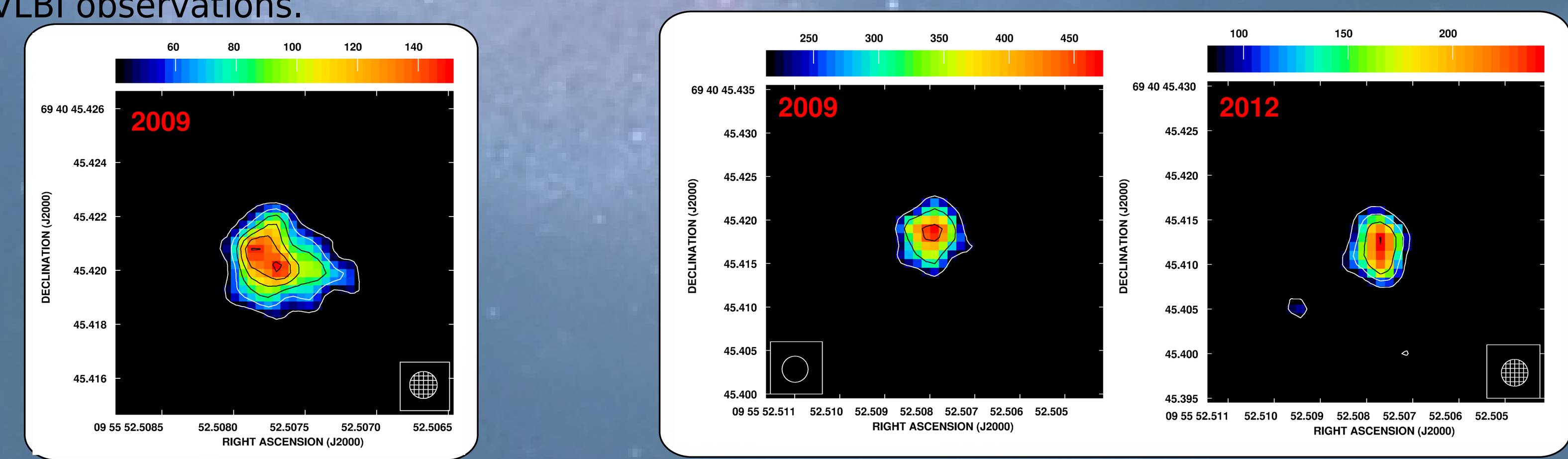
Evolution of the measured size with time for 43.31+59.2. The lines correspond to several potential deceleration parameters. The best-fit line is shown in red.

Below: EVN and global VLBI 1.7-GHz 15-mas images of 43.31+59.3 at multiple epochs.



The 'transient'

A new source was detected in MERLIN observations in May 2009 by Muxlow et al. (2010, MNRAS, 408, 607). This source was initially considered to be one of the population of transient sources to appear in M82. However, following its initial detection, 43.78+59.3 increased in flux density to ~700 mJy/bm within approximately eight days and remained at this level in subsequent observations. This source has been regularly monitored using MERLIN/e-MERLIN, eVLBI and global VLBI observations to determine the nature. A new radio supernovae is expected to undergo a rapid rise followed by a power-law decline with a progressive turn-on with frequency. However, 43.78+59.3 experienced a rapid rise in flux density to a constant level and appeared to have a steep spectral index at turn-on, which has also shown virtually no variation since. As a result this source does not appear to be a typical radio supernovae and the fundamental nature of this transient source remains unknown. Over the last few years the transient source has recently begun to decline in flux density and preliminary imaging suggests it is now undetectable in the most recent VLBI observations.



Global VLBI images of the transient source at multiple epochs. Left: 5-GHz, 1-mas resolution. Right: 1.7-GHz images at 3-mas resolution. Colour-scale is shown in microJy.

Muxlow et al. (2010) discussed several possibilities that could provide some explanation. These included a peculiar supernova event, a faint AGN at the centre of the galaxy or micro-quasar. However, none of these suggestions currently fully explain the observed characteristics. Muxlow et al. (2010) also reported a tentative detection of super-luminal motion of ~4.2c within the MERLIN monitoring observations of this source. This motion appeared to be in an east-west direction. As can be seen from the global VLBI images of the transient source (below), the 1mas 5GHz image shows a clear elongated structure in the east-west direction, consistent with the motion observed by Muxlow et al. (2010).