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Flux density variations of radio sources in M82

M. A. Gendre*
Jodrell Bank Center for Astrophysics
E-mail: mgendre@jb.man.ac.uk

D. M. Fenech
Department of Physics and Astronomy, University College London

R. J. Beswick
Jodrell Bank Center for Astrophysics

T. W. B. Muxlow
Jodrell Bank Center for Astrophysics

M. K. Argo
Netherlands Institute for Radio Astronomy (ASTRON)

M82 is one of the closest (D = 3.2 Mpc) starburst galaxies known, producing a large population of massive, rapidly evolving stars, and an equally large number of supernovae. We present here the results of the 2009-2010 monitoring sessions of the starburst galaxy M82, obtained with the Multi-Element Radio-Linked Interferometer Network (MERLIN) at 5 GHz and *e*-MERLIN at 6 GHz. Combining the 5-GHz MERLIN epochs to form a map with 33.0 μJy/beam noise level, 52 discrete sources, mostly supernova remnants and HII regions, are identified. These include three objects which were not detected in the 2002 5 GHz MERLIN monitoring session: supernova 2008iz, the transient source 43.78+59.3, and a new supernova remnant shell. Flux density variations, both in the long (1981 to 2010), medium (2002 to 2010) and short (2009 to 2010) term, are investigated. We find that flux densities of SNRs in M82 stay constant in most of the sample (90-95%). In addition, aside from SN2008iz and the well-known variable source 41.95+57.5, two sources display short term variations over the period 2009-2010.

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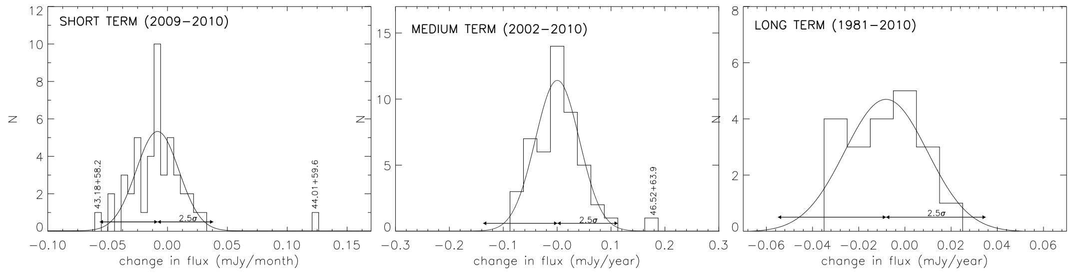

Figure 1: Short (over the 2009-2010 period, left), medium (over the 2002-2010 period, centre) and long (over the 1981-2010 period, right) term variability. Names correspond to sources with rates of change outside a 2.5σ limit of the distribution. SN2008iz and the variable source 41.95+57.5 lie well outside the range of this plot and are not represented.

1. Observations

The 2009 monitoring campaign of M82 consisted of seven wide-field MERLIN observations at a frequency of 4.994 GHz observed between May 2009 and April 2010. These were made using parallel hands of circular polarisation, and were correlated with a total bandwidth of 16 MHz divided into 32 channels. Across all epochs combined a total on-source integration time of 286.5 hours was used. Each observing epoch was reduced and analysed individually and a deep exposure map was produced by combining all of these data. In addition to these, a single *e*-MERLIN observation was included in this study. This observation was made in December 2010 as part of the *e*-MERLIN commissioning programme and used a total bandwidth of 512 MHz with a median frequency of 6.26 GHz. These data were correlated into four individual sub-bands each divided into 512 frequency channels. These *e*-MERLIN observations were observed prior the installation of the new *e*-MERLIN wide-band IF system in spring 2011 and subsequently only one hand of polarisation was used and the data displayed reduced sensitivity in parts of the observing band.

2. Source variability

To improve our analysis of flux density variation, archival 5 GHz MERLIN data from 2002 (Fenech et al. 2008) and 2005 (Argo 2006), as well as data taken over an 11-yrs period from 1981 (Kronberg et al. 2000) were added to the light curves when available. Changes in the flux density of the detected sources were studied in the short, medium and long term (over the 2009-2010, 2002-2010 and 1981-2010 periods respectively). A line S(t) (with t in month for short term and years for medium and long terms) was fitted through every light curve and the slope used to determine which sources displayed consistent flux density variations. The distribution of slopes was fitted with a Gaussian model (see Figure 1). Outliers (with rate of change outside of 2.5σ) indicate sources with noticeable variability (SN2008iz and the variable source 41.95+57.5, which show extreme variation, are not represented in these plots).

A total of five sources have shown flux density changes in the medium or short term, including 41.95+57.5, SN2008iz and the transient source 43.78+59.3. The two other varying sources (Figure 2) have small angular sizes, and are in fact the most compact SNR in M82 after 41.95+57.5

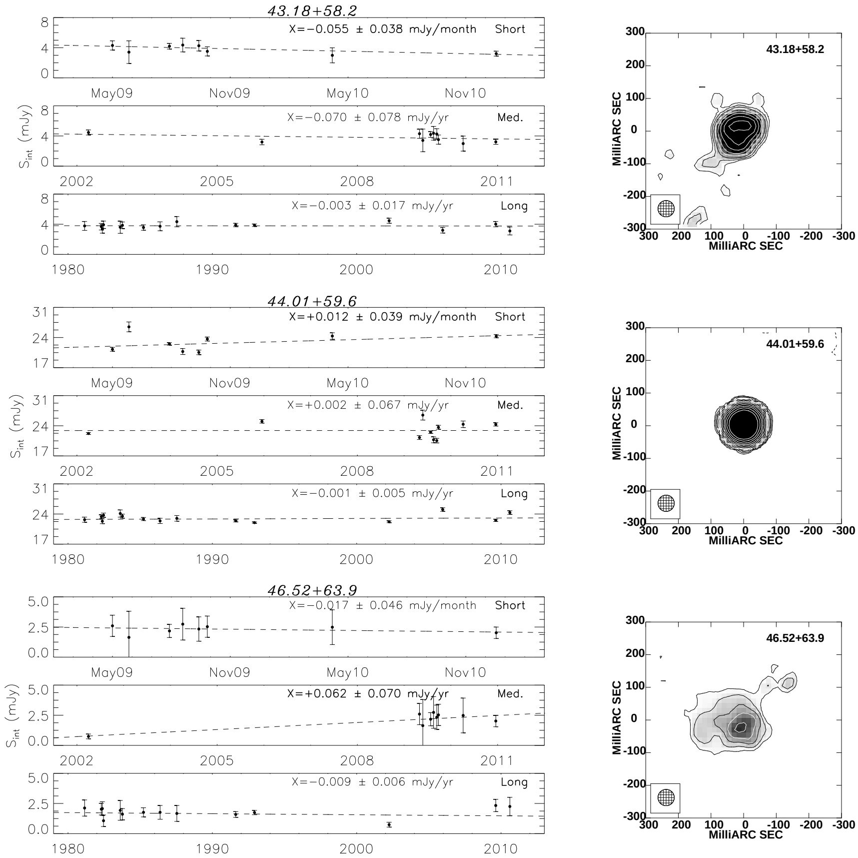

Figure 2: Left: Short, medium and long term light curves over the period 2009-2010 (top), 2002-2010 (centre) and 1981-2010 (bottom, where the 1981-1991 data were retrieved from Kronberg et al. 2000) for sources showing noticeable decrease in flux density (shown in bold font on the plots), aside from 41.95+57.5 and SN2008iz. For long term variation, flux measurements were averaged over EP1-6 for 2009 and EP7-8 for 2010. A line $S(t) = S_0 + Xt$ was fitted to each curve (dashed line), where X characterises the variation in mJy/month and mJy/yr for short and medium/long terms respectively. Right: Contour plot at -1, 1, 1.414, 2, 2.828, 4, 5.656, 8, 11.282, 16, 22.564, 32, 45.1286 $\times$ 99 μJy/bm of the source from the combined 2009-2010 MERLIN data. The beam size is shown in the bottom left-hand panel.

(Fenech et al. 2008). Based on expansion velocity measurements from VLBI and MERLIN data, Fenech et al. (2008) and Beswick et al. (2006) determined that these sources are amongst the youngest in M82, with ages of 55 and 140 yrs (as of 2002). Consequently, their short term brightness variations could be explained by changes in the circumstellar and interstellar mediums in which the shocks travel, with these sources being at a different temporal stage in their evolution, compared with the older more stable sources. Note that a third source showing variation, 46.52+63.9, was excluded from the varying sample as it does not show any signs of variability in the short or long term and its variation can be explained by an anomalously low value of the source flux density measured in 2002.

SNRs in M82 are expected to be the result of core-collapse supernova events with a massive, typically red supergiant (RSG), progenitor star (Fenech et al. 2010). At the time of the supernova explosion, there will be a complex circumstellar environment consisting of a slow-moving dense

RSG wind followed by a wind-blown bubble of almost constant low density produced by the main-sequence low-density, high-velocity wind. It is generally accepted that following the evolution through the wind-blown bubble, it is likely that there will be a marked peak in flux density as the supernova ejecta travels from the low-density wind-blown bubble into the higher density ISM (particularly in the case of M82). This will primarily be caused by the production of a thin-dense shell at the edge of the wind-blown bubble. There will however, also be a subsequent decline in flux density as the ejecta traverses this shell and emerges into the ISM, traditionally considered the transitional phase from a supernova to a supernova remnant. It is possible that this could provide an explanation for the observed flux-density decay. Continued regular monitoring of these sources will give us more insights to their behaviour. It is now possible to carry this out with new sensitive instruments such as *e*-MERLIN and the EVLA, and we expect to get a more complete view of the evolution of SNRs in M82.

3. 41.95+57.5 - Known variable

This source has shown a continued decrease in flux density of 8.8%/yr since its first observation in 1965 (Trotman 1996). This decay rate would imply that, at birth, the source would have had a flux density of 30 Jy. These two facts (continuous decay and high flux density at birth) suggest that 41.95+57.5 is likely to be an exotic event and several suggestions have been made as to its nature, including the possibility that it may have been an off-axis gamma-ray burst (Muxlow et al., 2005).

As seen in Figure 3, 41.95+57.5 still shows a steady decrease in flux density. However, its rate of change seems to have decreased from 8.8%/yr to closer to 7.8%/yr. VLBI observations of 41.95+57.5 in November 1998 and February 2001 shows the source to be expanding at a rate of $\sim$2000$\pm$500 km s^{-1}. However, further VLBI data from 2005 shows that the apparent radius of 41.95+57.5 may have decreased between 2001 and 2005 (30.4 mas in 2001 and 26.85 mas in 2005).

The unusually luminous radio supernova 1986J in NGC891 and 41.95+57.5 show some distinct similarities. Both sources display an asymmetric radio structure on milliarcsecond scales, modest expansion velocities, relatively high initial radio luminosities and a power-law flux density decay (Bietenholz et al. 2010). Both the possible decrease in apparent angular size and the small deviation from the historical flux density decline of 41.95+57.5 in these recent 5 GHz flux density measurements are consistent with the potential appearance of a new higher frequency central component within the shell. As such, this source may be undergoing an evolution analogous to that observed in SN1986J, albeit in a much older remnant. Unfortunately, the MERLIN and *e*-MERLIN observations presented here do not have adequate angular resolution to image in detail the structure of this source and, as yet, higher frequency ($>$1.6 GHz) VLBI observations have not confirmed this hypothesis. Further analysis of the variation in flux densities of 41.95+57.5 and SN1986J, both in time and frequency, would be needed to assess the similarity between the sources.

4. SN2008iz

The light curve of SN2008iz from the presented MERLIN data and supplemented by data

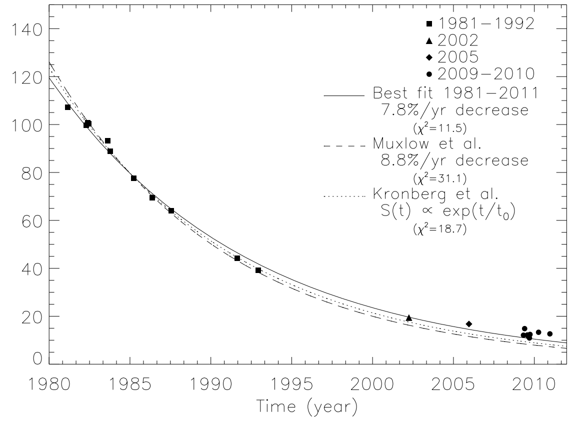

Figure 3: Light curve for the source 41.95+57.5 over the period 1981-2010. Data for each period were retrieved as follow: 1981-1991 from Kronberg et al. 2000, 2002 from fenech et al., 2008, 2005 from Argo 2006, 2009-2010 from this work. Models for the flux density decrease are based on an exponential decay (dotted line - Kronberg et al. 2000), an 8.8%/yr decay (dashed line - Muxlow et al. 2005) and our best fit 7.8%/yr decay (solid line).

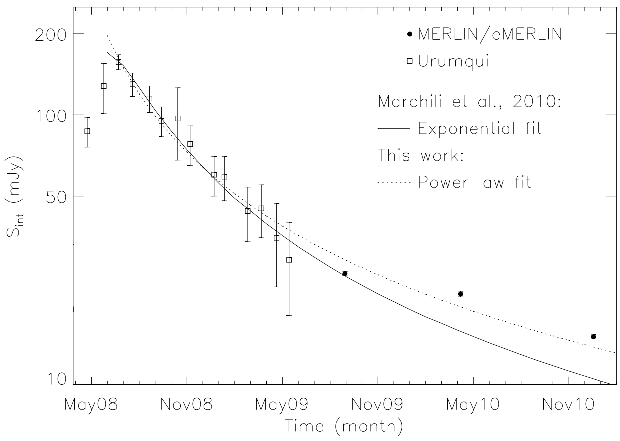

Figure 4: Light curve for SN2008iz. 5 GHz data from single dish Urumqi observations (Marchili et al., 2010) and the MERLIN/*e*-MERLIN data are shown as open squares and filled circles respectively. An exponential decay model was fitted to the curve using parameters from Marchili et al. (2010) - solid curve - as well as a power-law decay model - dotted curve - which displays the best fit to the decay part of the curve.

from Marchili et al. (2010) is shown in Figure 4. Following Marchili et al. (2010), the flux density decline after reaching peak brightness can be modelled using an exponential decay:

$$S(t) = K_1(t-t_0)^{\beta} e^{-\tau} \qquad \tau = K_2(t-t_0)^{\delta} \tag{4.1}$$

where t_0 is the explosion date, which was fitted to be February 18, 2008 (Marchili et al., 2010).

The 2009-2010 data display a flattening of the light-curve which does not seem to be properly fitted by an exponential model. A power-law decay of the form

$$S(t) \propto (t-t_0)^{\alpha} \tag{4.2}$$

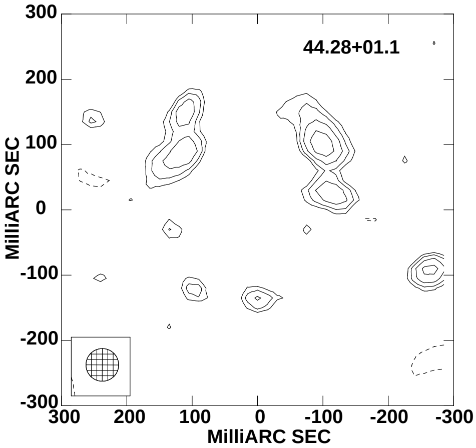

Figure 5: Contour plot at -1, 1, 1.414, 2, 2.828, 4, 5.656, 8, 11.282 × 99 μJy/bm of SNR 44.29+01.1. The beam size is shown in the bottom left-hand panel.

where $\alpha = -1.24 \pm 0.06$, shows a better fit to the flux-density decrease, with a χ^2_{red}=10.97 while the exponential fit of [**?**], including the 2009-2010 data, yields χ^2_{red}=92.6.

Whilst further later time measurements are required to confirm these results, there is tentative evidence that the radio light curve of SN2008iz is showing a small reduction in the rate of its flux density decline.

5. 44.29.01.1 - A newly detected SNR shell

In order to search for possible new sources, each of the 51 known sources in M82 (Fenech et al. 2008) were imaged and subtracted from the uv-data. The resulting dataset was then re-imaged. Following inspection of this new image, one new source was identified. This source, located at position 09 55 53.00 +69 40 47.24 (J2000), has a peak flux density value of S_{peak}=0.17 mJy/bm and an integrated flux density of 0.37±0.11 mJy. Being shell like in shape (Figure 5), it is most likely a supernova remnant.

By measuring the source extent, the age of the SNR can be inferred. The radius of the source was determined to be r=140±5 mas. At the distance of M82 (3.2 Mpc), this gives an estimated radius of 2.1 pc. Fenech et al. (2008) measured expansion velocities of SNRs in M82 to be between 2200 and 10500 km/s, with a mean velocity of v_{exp} = 5650 km/s. Using the latter value, we can estimate the age of 44.28+61.1 to be ∼360 yrs.

6. Conclusion

We presented the results of the 2009-2010 monitoring sessions of the galaxy M82, obtained with MERLIN and *e*-MERLIN at 5 and 6 GHz respectively. The data include eight epochs between May 2009 and December 2010, and were compared with data from the April 2002 monitoring session of Fenech et al. (2008).

A total of 52 sources were detected, including three sources absent from the 2002 data: supernova SN2008iz, the transient source 43.78+59.3 and a new SNR shell, 44.29+01.1. Although the first two were previously observed, the latter was first detected here.

Light curves for all sources have been compiled, including flux density measurements from 2002 (Fenech et al. 2008), 2005 (Argo 2006) and these new 2009-2010 data from 5 GHz MERLIN monitoring sessions. We have found that, in most of the sample, flux densities of SNRs in M82 stay relatively constant, in agreement with previous analysis (e.g. Kronberg et al. 2000). Aside from SN2008iz and the well-known variable source 41.95+57.5, two sources show signs of changes in flux density in the short term.

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