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Discovery of an unusual new radio source in the star-forming galaxy M82: Faint supernova, supermassive blackhole, or an extra-galactic microquasar?

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ABSTRACT

A faint new radio source has been detected in the nuclear region of the starburst galaxy M82 using MERLIN radio observations designed to monitor the flux density evolution of the recent bright supernova SN 2008iz. This new source was initially identified in observations made between 1-5th May 2009 but had not been present in observations made one week earlier, or in any previous observations of M82. In this paper we report the discovery of this new source and monitoring of its evolution over its first 9 months of existence. The true nature of this new source remains unclear, and we discuss whether this source may be an unusual and faint supernova, a supermassive blackhole associated with the nucleus of M82, or intriguingly the first detection of radio emission from an extragalactic microquasar.

Key words: galaxies: starburst, M82, radio continuum: stars, supernovae

1 INTRODUCTION

The nearby (d=3.6 Mpc; Freedman et al. 1994) star-forming galaxy M82 has been subject to frequent radio monitoring at centimetric wavelengths with the VLA from the early 1980s (Kronberg, Biermann & Schwab 1981, 1985), and with MERLIN from the early 1990s (Muxlow et al. 1994; Pedlar & Muxlow 1995). Of order 60 compact radio sources have been identified within the central kpc of M82, the majority of which are thought to be recent supernova remnants which have exploded within the last 2000 years. The origin of 46 of these objects has been determined by the study of their radio spectral indices; 30 are considered to be supernova remnants, and 16 are thought to be compact H II regions (McDonald et al. 2002).

Radio monitoring at intervals of around a year has shown that there is an additional population of radio transient sources whose origin is unknown. To date two transient sources have been detected, and each for only a single monitoring epoch implying that their lifetimes are typically less than a year. Kronberg & Sramek (1985) detected the compact radio source 41.5+597 in M82 with the VLA in February 1981. At that epoch, the object had a flux density of 7.1 mJy and 2.6 mJy at wavelengths of 6 and 2 cm respectively, implying that the source possessed a steep radio spectral index of α=−0.9 (S=ν^{α}). By October 1983 the source had faded to below the detection threshold of their VLA monitoring observations with an upper limit of 1.5 mJy at 6 cm. In a series of 6 cm MERLIN monitoring observations starting in the early 1990s, no emission was found at the position of 41.5+597 to limits of ∼60μJy, and in the deepest 6 cm MERLIN observations of M82 to date, made in 2002 (Fenech et al. 2008) no emission was found to a limit of 20 μJy.

In July 1992 Muxlow et al. (1994) detected a second transient, 40.59+55.8 with MERLIN at 6 cm with a flux density of 1.2 mJy. Subsequent MERLIN monitoring at 21 cm in April/May 1993 failed to detect emission at the position of the transient to a limit of 300 μJy. Furthermore it was

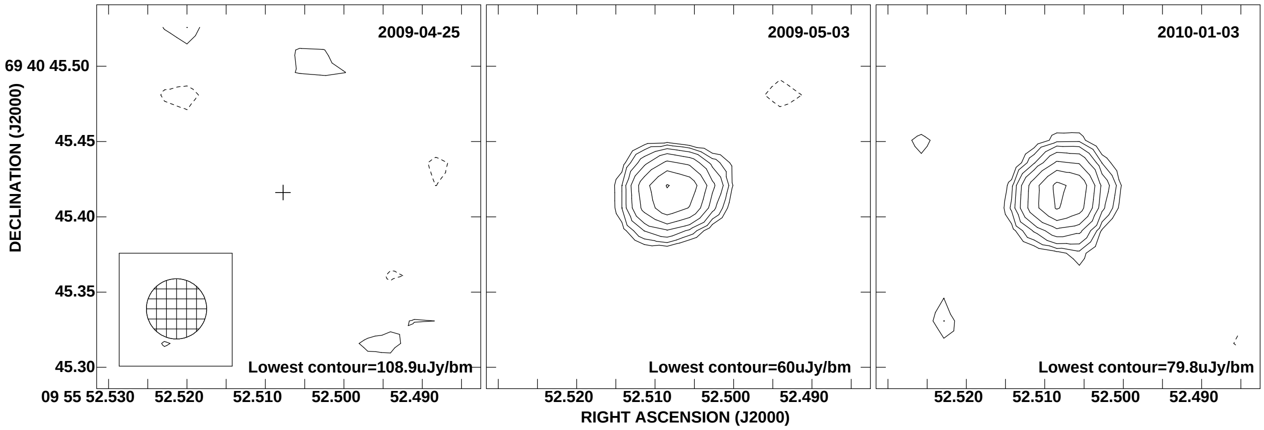

Figure 1. Images at the position of the new radio source in 3 epochs observed with MERLIN at 4994 (first two epochs) and 6668.4 MHz (final epoch). All images have been convolved with a circular 40 mas beam as shown in the bottom left of the first panel. The positional cross in first panel is the fitted position to Epoch 2 (1-5th May 2009). Each image has been contoured in a similar manner with levels increasing by a factor of $\sqrt{2}$ times the lowest contour level, which is labeled in each panel.

not detected by deep MERLIN imaging at 6 cm in February 1999 and April 2002 with limits of 35 and 21 μJy respectively (McDonald et al. 2002; Fenech et al. 2008). Both 41.5+597 and 40.59+558 lie outside the dynamical centre of M82 and since neither has given rise to a radio supernova remnant, they may be examples of stellar binary microquasar systems. If so, they would be the first to be discovered in the radio outside the Milky Way.

Recently, Brunthaler et al. (2009a,b) reported the detection of radio emission from a new bright supernova in M82 (SN 2008iz) which is thought to have flared during the last week of March 2008 (Marchili et al. 2010). The appearance of SN 2008iz around 45 years after the previous supernova (43.31+592, Beswick et al. 2006) is consistent with the radio supernova rate for M82 of a new supernova approximately every 15 to 30 years (Muxlow et al. 1994; Fenech et al. 2008). Subsequent enhanced MERLIN monitoring of M82 has resulted in the detection of a new radio source in the central region of the galaxy (Muxlow et al. 2009). This faint new radio source was discovered in observations taken 1-5th May 2009 and was not present in images taken ∼1 week earlier, on the 25th April 2009 (see Fig. 1). Using closely spaced MERLIN (and VLBI) observations between April 2009 and January 2010, it has been possible, for the first time, to study the detailed evolution of one of the M82 transient source population.

2 OBSERVATIONS AND DATA REDUCTION

The detection of both this new source and the campaign of continued flux density monitoring of the evolving SN 2008iz motivated a series of radio monitoring observations of M82. MERLIN observations of M82 were made between late April 2009 and January 2010 at 4994 and 6668.4 MHz, and 1658 MHz.

All observations were made in wide-field mode, with parallel hands of circular polarisation, measured over 16 MHz of bandwidth correlated into 32 frequency channels. The primary flux density calibrator 3C 286 was used to set the flux density scale and the unresolved bright calibrator OQ208 was used to calibrate the amplitudes and bandpass responses. Throughout each epoch observations were interspersed with scans on the nearby phase reference source J095910+693217, with an assumed position of RA $09^{\mathrm{h}}\,59^{\mathrm{m}}\,10\overset{\mathrm{s}}{.}6391$, Dec $69^{\circ}\,32'\,17\overset{''}{.}723$ (J2000).

Data from each epoch were independently reduced using standard methods applying phase corrections determined form the phase reference source, J095910+693217, and the data were weighted appropriately to account for the relative sensitivities of the individual antennas. Following calibration, a large field encompassing the entire radio extent of M82 at this resolution was imaged, using multiple imaging facets and fully accounting for wide-field imaging effects. At each different reference frequency all epochs were imaged in an identical manner and the images were restored with a circular Gaussian beam appropriate for the *uv* spacing of the baseline lengths and the weighting applied to the gridded data during imaging.

3 RESULTS

3.1 Radio lightcurve

Radio lightcurves of the new MERLIN radio source are shown in Fig. 2, along with a composite MERLIN and Urumqi 5 GHz light curve for SN 2008iz (Marchili et al. 2010; Beswick et al. 2009). The Urumqi 5 GHz observations do not resolve M82, but the observed variations in the total flux density are dominated by SN2008iz. The new MERLIN radio source reached a flux density of ∼600-700 μJy at 4994 MHz by early May 2009, showing greater than a factor of 5 increase in flux density within 8 days. The flux density of the source has remained approximately constant throughout all subsequent observations. Simultaneous VLBA observations at 1.6 and 4.8 GHz observed on 30th April 2009, 3 days prior to the initial MERLIN 5 GHz detection, show this source to have an initial spectral index of −0.7 (Brunthaler et al. 2009d). MERLIN monitoring obser-

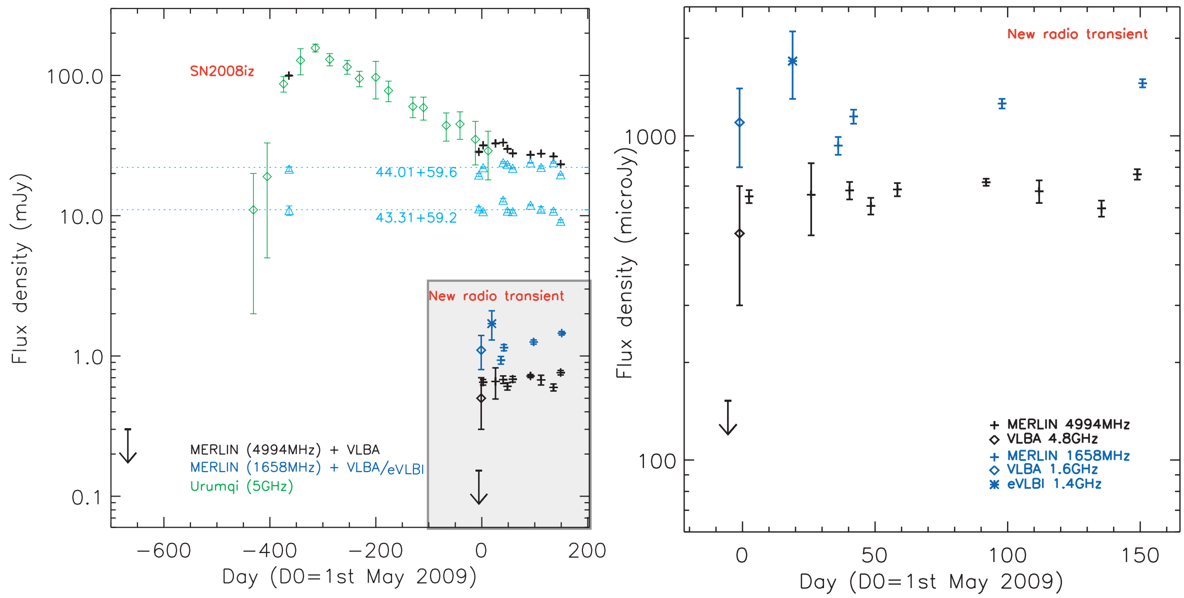

Figure 2. The *left-hand panel* shows the radio light curve of SN 2008iz and the new transient source reported over the first 150 days of its existence. MERLIN 4994 and 1658 MHz data are plotted as black and blue crosses respectively. MERLIN observations at 6666.8 MHz are not plotted. 1.4 GHz eVLBI data are shown as blue stars, 5 and 1.6 GHz VLBA are shown as black and blue open diamonds respectively (Brunthaler et al. 2009d). The 5 GHz light curve for the SN 2008iz (Marchili et al. 2010) derived from single dish Urumqi observations is shown in green. The flux densities measured from these MERLIN data at 5 GHz for two nearby compact remnants 44.01+59.6 and 43.31+59.2 which are known to have a constant flux density (Kronberg & Sramek 1985; Ulvestad & Antonucci 1994) are also shown as pale blue triangles. An enlargement of the shaded region showing the light curve for the new radio transient is shown in the *right-hand panel*.

vations at 1658, 4994 and 6668.4 MHz show no significant variations in the spectral index of this source throughout its first 150 days.

The evolution of the radio light curve for SN 2008iz, (left-hand panel of Fig. 2 and discussed in detail by Marchili et al. 2010), is typical for a core-collapse supernova, showing a rapid rise in flux density followed by a power-law decline (see for example Weiler et al. 2002). In comparison the new MERLIN radio source is ∼100 times fainter than SN 2008iz, and shows significantly different flux density evolution with little or no detectable variation following a very rapid initial rise.

3.2 Position and size of this new radio source

This new MERLIN source was detected on 3rd May 2009 at a position of RA $09^{\mathrm{h}}\,55^{\mathrm{m}}\,52\overset{\mathrm{s}}{.}5083$, Dec $69^{\circ}\,40'\,45\overset{''}{.}410$ (J2000) with an astrometric error of 5 mas in each coordinate. This position is within 3 mas of the VLBA detection of this source on the 30th April 2009 (Brunthaler et al. 2009d).

The position of the new MERLIN source has been measured in each epoch relative to the position of the phase reference source and relative to other bright, static radio sources in M82, such as SN 2008iz, 41.95+57.5, 43.31+59.2 and 44.01+59.6. Over the first 50 days of monitoring, including 6 MERLIN and 3 VLBI epochs, the fitted position of the source shows evidence for east to west proper motion of ∼10±5 mas. This equates to an apparent proper motion of ∼0.2 mas day^{-1}, equivalent to an apparent superluminal motion of ∼4.2c at the distance of M82. Subsequent data from 29th June 2009 (58 day after 1st May 2009) onwards show the source position to be consistent with its initial position measured on 3rd May 2009. Thus, considering that the positional shift is at the limit achievable with these data the detection of any proper motion can only be considered as tentative at this early epoch.

The highest resolution image with MERLIN was observed on 3rd January 2010, 247 d after 1st May 2009, at a frequency of 6.7 GHz. From these data the source is partially resolved with a deconvolved Gaussian fitted size of 15^{+5}_{-6} mas.

4 DISCUSSION: NATURE OF THIS NEW RADIO SOURCE

Historical transients 41.5+597 (Kronberg & Sramek 1985) and 40.59+558 (Muxlow et al. 1994) were each detected in only one monitoring epoch implying lifetimes of less than a few months to a year. The new transient is broadly similar to the earlier detections in flux density (within a factor of 10) and spectral index, although its longevity may soon indicate that it is a different type of object. To date, beyond the radio detection reported here, no confirmed detections of this new source has been made at any other waveband in either archival or contemporaneous observations, including X-ray (Kong & Chiang 2009) and at K-band using Gemini (Fraser et al. 2009) and the Nordic Optical Telescope (S. Mattila, private comm.).

We must consider the possibility that the new object is a background radio source that has brightened significantly.

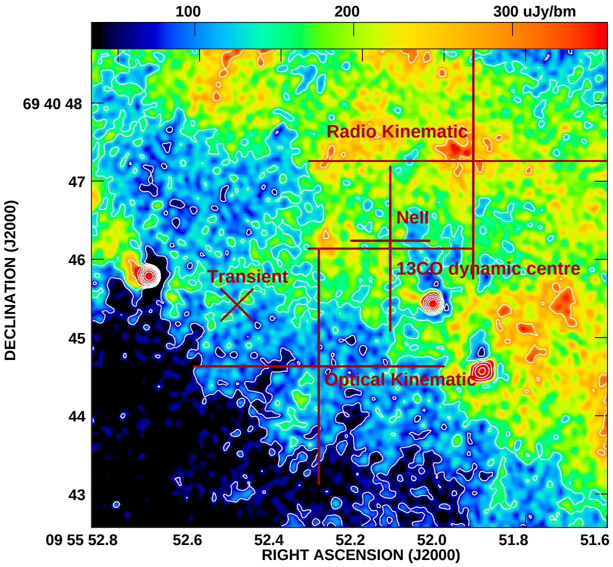

Figure 3. Combined MERLIN and VLA 5 GHz false colour image of the region surrounding the new radio source location, taken prior to its discovery. The position of the new source is marked by an X (size not equal to the astrometric error). The position with associated errors of the dynamical centre of M82 derived via several multiwavelength methods (Weliachew et al. 1984) are also shown as plus signs (+). The two brightest compact radio sources in this image are 44.01+59.6 (left) and 43.31+59.2 (right).

The area of sky that has been subjected to monitoring observations is the central nuclear ∼1 kpc of M82, an area of approximately 45×15 arcsec in extent. The probability of finding a background AGN system of ∼1 mJy at 5 GHz within this area is ∼1 in 550 (Prandoni et al 2006). However, this object is extremely unusual in that it has brightened by at least a factor of 5 (detection flux density/3σ non-detection flux density) on a timescale of ∼1 week. Since <1% of the faint background source population exhibit such violent intrinsic variability, this reduces the probability by at least two orders of magnitude (e.g. Carilli, Ivison & Frail 2003).

The position of this new source lies at high Galactic latitude (+40°). Considering this and the fact that no detection of this new source has been made in any other waveband this source is consistent with being either extremely optically faint and/or highly obscured by material within M82. Thus on the balance of probability, we conclude that the new transient is neither a foreground or background source and that it must lie within M82.

4.1 A faint and unusual radio supernova?

Typically radio supernovae emit high brightness temperature synchrotron emission which initially is absorbed at longer wavelengths. As the supernova shell expands this absorption decreases resulting in a rapid turn-on of emission at shorter wavelengths followed by a later turn-on at longer wavelengths, with an associated evolution in radio spectral index. After reaching its peak luminosity a supernova then normally follows a power-law decline (e.g. SN 2008iz. Fig 2 and Weiler et al. 2002).

The peak luminosity of this new source at 5 GHz is $\sim1\times10^{18}$ W Hz^{-1}. This is 3 orders of magnitude less than the peak observed from Type-Ib/c supernovae and comparable to the limits on the radio emission from Type-Ia supernovae, which so far have not been detected (Panagia et al. 2006). Whilst this source is two orders of magnitude fainter than SN 2008iz (see Fig. 2), its luminosity is comparable to some faint nearby Type-II radio supernovae (e.g. SN 2004dj, SN 1987A; Beswick et al. 2005; Turtle et al. 1987). The peak luminosity and the rise time of Type-II supernovae can be empirically related (see Eq. 20 of Weiler et al. 2002). Following this relationship a source of this luminosity should reach its peak flux density at 5 GHz between 3 and 11 days after the supernova detonation. This timescale is consistent with the rise time observed (Fig. 2) and supports the scenario that this source is a Type-II supernova.

However, there are several observational discrepancies with the hypothesis that this is a faint supernova. Firstly, following the very rapid initial rise in flux density (Figs. 1, 2) the light curve for this object shows no significant evolution and in particular no power-law decline. Whilst this is not common for supernovae (Weiler et al. 2002), a plateau in the radio light curve as observed here could result from the expanding supernova shell interacting with a denser interstellar medium at later times. Thus, whilst atypical, this lack of power-law flux density decay cannot rule out the supernova hypothesis. Secondly the spectral index as measured via simultaneous multi-frequency observations prior to the source reaching its peak flux density was −0.7 and has shown no apparent evolution in the subsequent 150 days. This characteristic is in contrast to spectral evolution expected for young radio supernovae, and can only be accounted for if the source had already evolved past its peak at centimetre radio frequencies before 30th April 2009.

The initial expansion velocities of typical radio supernovae have been measured to be ∼23,000 km s^{-1} (e.g. SN 2008iz Brunthaler et al. 2009c, 2010; Weiler et al. 2002, and references therein). Thus at an age of ∼250 days a radio supernova would typically have an angular size of $\lesssim$2 mas at the distance of M82. Our most recent and highest resolution observations were taken on 3rd January 2010, when the source was at least 250 days old. At this epoch the source is tentatively resolved with a Gaussian fitted size of 15^{+5}_{-6} mas (see Section 3.2). If this source is a supernova this size would require either a mildly relativistic expansion velocity (similar to that recently reported for SN2007gr and SN2009bb, Paragi et al. 2010; Soderberg et al 2010) or that its age is significantly underestimated.

4.2 Accretion around a massive collapsed object?

The steep radio spectral index from birth (and the possible detection of apparent superluminal motion) supports the hypothesis that the transient may be associated with an accretion disc around a massive collapsed object in the nuclear region of M82. We suggest two possible scenarios.

4.2.1 An AGN in the nucleus of M82

The transient lies close to, but a few arcsec to the West of the dynamical centre of M82 as derived from radio, optical, NeII, and ^{13}CO kinematic studies (Weliachew, Fomalont & Greisen 1984, see Fig. 3). The position is also displaced from the ridge-line of the extended radio emission which is thought to be associated with the integrated emission from ejected plasma over the recent star-formation history of M82. Unless the region of nuclear star-formation and the dynamical centre are significantly displaced from the centre of the gravitational potential, it would seem unlikely that this object is associated with a central super-massive black hole (SMBH) in M82. Emission from such an object has, to date, never been detected. It is possible that this could be emission from a system associated with a second SMBH absorbed from a dwarf galaxy merging with M82, but there is no supporting evidence of such a merger from observations; however M82 is very disturbed and is interacting with other galaxies in the M81-M82 group (Yun, Ho & Lo 1994).

4.2.2 Radio emission from an extragalactic microquasar?

Alternatively this source may be result of some form of flaring microquasar event in M82. The 700 μJy flux density of this source in M82 is equivalent to a $\sim$90 Jy source at a distance of 10 kpc. The brightest microquasar flares that have been seen in the Galaxy at centimetric wavelengths are from Cygnus X-3 which flares to several tens of Jy (Gregory & Kronberg 1972). However, whilst such flares are close to the required luminosity seen in the transient, the light curves of known Galactic microquasars differ significantly from that seen for this object with Galactic flares peaking and then decaying away on a timescale of days to weeks. The radio luminosity of the transient is comparable with the ultraluminous X-ray source found in the nearby dwarf galaxy NGC 5408 (Lang et al. 2007). Both objects possess a steep radio spectral index, however to date, no variable X-ray source has been detected at this position in M82.

Some form of relativistic jet could account for the observed steep spectral index since in Galactic microquasars any optically thick state typically evolves to thin within hours of turn on (Mirabel & Rodrìguez 1999; Fender & Belloni 2004). This scenario is compatible with the possible detection of superluminal proper motion and the elongation seen at late times. The strong jet-disk coupling would thus imply the presence of an accretion disk around a massive collapsed object, although the nature of this collapsed object remains unclear. If the transient is some form of microquasar, its luminosity suggests that it is likely to be associated with a massive black hole system of some type. This could range from an extreme form of X-ray binary to an intermediate-mass black hole system. However, the very high luminosity and temporal longevity of the transient imply that this type of accretion object is unusual and has not yet been seen within our Galaxy.

5 CONCLUSIONS

This new source could be any of the above possibilities although each of the proposed scenarios has difficulty in explaining all of the observed properties. At present this source has been detected for >9 months and shows no immediate signs of fading. Depending upon its longevity it may represent another example of a relatively short-lived faint radio source population in M82. If so it would be the third example seen in $\sim$30 years of observations; thus a lower limit on their occurrence rate is $\sim$1 every 10 years, depending on their lifetimes. If this population is associated with faint supernovae it will have significant implications on the radio derived supernova rate of M82. Alternatively if this source is associated with microquasar flare event and the occurrence of which is related to the host galaxies star-formation rate, we would expect to see a comparable event in our own Galaxy around 1 every 100 years. Regular monitoring observations with new sensitive, high resolution imaging arrays, such as e-MERLIN and the EVLA, will be required to determine the size and nature of any such a population, both M82 and other star-forming galaxies.

Global VLBI observations at 1.6 and 5 GHz with milliarcsecond resolution were taken in late 2009 and are awaiting correlation. Images of the transient from these new data will constrain the nature of this exciting source.

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