Supernovae and radio transients in M 82

S. Mattila*1,2, M. Fraser3, S.J. Smartt3, W.P.S. Meikle4, C. Romero-Cañizales2, R.M. Crockett3,5, A. Stephens6
1 Finnish Centre for Astronomy with ESO (FINCA), University of Turku, Väisäläntie 20, FI-21500 Piikkiö, Finland.
2 Tuorla Observatory, Department of Physics and Astronomy, University of Turku, Väisäläntie 20, FI-21500 Piikkiö, Finland.
3 Astrophysics Research Centre, School of Mathematics and Physics, Queen’s University of Belfast, Belfast BT7 1NN, UK.
4 Astrophysics Group, Blackett Laboratory, Imperial College London, Prince Consort Road, London, SW7 2AZ, UK.
5 Oxford Astrophysics, Department of Physics, Denys Wilkinson Building, Keble Road, Oxford, OX1 3RH, UK.
6 Gemini Observatory, 670 North Aohoku Place, Hilo, HI 96720, USA.

ABSTRACT
We present optical and near-infrared (IR) photometry and near-IR spectroscopy of SN 2004am, the only optically detected supernova (SN) in M 82. These demonstrate that SN 2004am was a highly reddened type II-P SN similar to the low luminosity type II-P events such as SNe 1997D and 2005cs. We show that SN 2004am was located coincident with the obscured super star cluster M 82-L, and from the cluster age infer a progenitor mass of $12^{+7}_{-3} M_{\odot}$. In addition to this, we present a high spatial-resolution Gemini-N K-band adaptive optics image of the site of SN 2008iz and a second transient of uncertain nature, both detected so far only at radio wavelengths. Using image subtraction techniques together with archival data from the Hubble Space Telescope, we are able to recover a near-IR transient source coincident with both objects. We find the likely extinction towards SN 2008iz to be not more than $A_V \sim 10$. The nature of the second transient remains elusive and we regard an extremely bright microquasar in M 82 as the most plausible scenario.

Key words: supernovae: general - supernovae: individual (SN 2004am; SN 2008iz) - galaxies: starburst - galaxies: individual (M 82) - infrared: galaxies.

1 INTRODUCTION
In the nuclear regions of M 82 and other nearby starburst galaxies one core-collapse supernova (CCSN) is expected to explode every 5-10 years and a number of young supernova remnants (SNRs) have been revealed in these regions by radio observations (e.g., Mattila & Meikle 2001). Searches working at near-infrared (NIR) wavelengths have discovered SNe in the nuclear and circumnuclear regions of a few nearby starburst galaxies and luminous infrared galaxies (LIRGs) (e.g., Kankare et al. 2003; Maiolino et al. 2002). Furthermore, optical searches have been able to discover a few SNe in normal nearby spiral galaxies with several magnitudes of visual extinction (e.g., SNe 2002hh, 2002cv; Pozzo et al. 2006; Di Paola et al. 2002).

The first claim of a detection of a supernova at optical or NIR wavelengths in M 82 was by Lebofsky et al. (1986), who reported the discovery of SN 1986D in 2 $\mu$m observations. However, it was later shown by Gehrz et al. (1986) that the source identified as SN 1986D was already present in their 2.2 $\mu$m images obtained three years earlier and has not varied significantly in brightness since then. This source was designated as the feature K2 by Dietz et al. (1986). SN 2004am in M 82 was discovered by the Lick Observatory SN Search (LOSS) on images from 2004 Mar. 5.2 UT but it was already present in their earlier images from 2003 Nov. 21.6. Being on a bright spot in M 82 caused their detection software to initially miss the new object. On 2004 March 6.9 SN 2004am was spectroscopically classified as a highly reddened type II event showing some spectral similarity to the type II-P SN 1995V (Mattila et al. 2004). Radio non-detections of SN 2004am on 2003 Nov. 14 (8.4 and 15 GHz) and on 2004 March 9 (5 GHz) were reported by Beswick et al. (2004). SN 2004am is still the only SN ever discovered at optical/IR wavelengths in M 82.

Being a prototypical starburst galaxy at a distance of 3.3±0.3 Mpc, (from the Cepheid distance to the M 81 group;
2001) means that there is a wealth of ground and space based imaging of M 82. Identification of progenitors in both Hubble Space Telescope (HST) and ground-based images has now become frequent (e.g., Smartt et al. 2004; Li et al. 2006; Mattila et al. 2008; Maund & Smartt 2009; Fraser et al. 2011; Van Dyk et al. 2012). Furthermore, in M 82 the compact star population has been studied extensively (e.g., Lançon et al. 2008; Bastian et al. 2007; Smith et al. 2006; McCrady et al. 2003). Hence SN 2004am is interesting not just because it is the first SN discovered in M 82 in the optical and NIR, but also because its physical association with the well studied super star cluster (SSC) M 82-L allows a mass estimate of the progenitor star. In one recent case, SN 2004dj in NGC2403, the explosion was coincident with a young compact star cluster (Maíz-Apellániz et al. 2004; Wang et al. 2005). The spectral energy distributions of the host cluster suggest ages and masses 13-20 Myr and 2.4-9.6×10^7 M⊙. If we assume that the stellar population in the cluster is coeval, then this leads to estimates of the progenitor mass of 12-15M⊙ (Vinkó et al. 2009) produced an improved study of the host cluster once SN 2004dj faded using extensive data from the UV to NIR. They estimated a most likely turn-off mass of between 12 and 20 M⊙. SN 2004dj was a type II-P (Vinkó et al. 2006), and the estimate of the progenitor mass from the turn-off age is consistent with the mass estimates from the direct detection of SN II-P progenitors on pre-explosion images (Smartt et al. 2009).

Over the last thirty years, there have been four detected radio transients in M 82 which have been suggested to be SNe. The source 41.5+59.7 (Kronberg & Sramek, 1985) was seen in February 1981 at 5 GHz with a flux density of 7.07±0.24 mJy, but by April of the following year had faded below the detection limit of 1.5 mJy. Another transient 40.59+55.8 (Muxlow et al. 1994) was detected at one epoch with the Multi-Element Radio Linked Interferometer Network (MERLIN) at 5 GHz with a flux density of ∼1.23 mJy in July 1992. Neither of these two sources were detected by Fenech et al. (2008) to a flux limit of ∼20 μJy, suggesting them to be transient sources, as opposed to sources with variable nature.

More recently, a bright (∼100 mJy) radio transient in the nuclear regions of M 82 was discovered by Brunthaler et al. (2009) in 22 GHz images from the Very Large Array (VLA) obtained in March 2008. Over one year’s time the source faded by a factor of ten, showing a spectral index of about −0.8 in the VLA (1.4-43 GHz) observations from April 2009 indicating an optically thick synchrotron spectrum. Furthermore, very long baseline interferometry (VLBI) observations from May 2008 and April 2009 revealed a ring-like structure expanding by ∼23 000 km s^{-1} (Brunthaler et al. 2010). These observations definitely confirmed the SN nature of the transient designated as SN 2008iz. Monthly monitoring of M 82 with the 25 m Urumqi radio telescope at 5 GHz led to the detection of SN2008iz as a flare on top of the M 82 radio emission (Marchili et al. 2010). The SN peaked with a flux of ∼160 mJy on 21st June 2008, while modelling of its light curve yielded an accurate explosion date of 18th February 2008.

In May 2009, another new radio transient was discovered in the nuclear regions of M 82 by means of MERLIN observations (Muxlow et al. (2009)). Following Gendre et al. (2012) we call it the 43.78+59.3 transient. This source reached a peak intensity of 0.72 mJy at 5 GHz in early May 2009, and 1.7 mJy at 1.6 GHz on 20th May 2009. The nature of this object is still unknown due to its peculiar low luminosity, its longevity (still observed after nine months of its discovery), its position with respect to the dynamical centre of the galaxy, and tentative evidence of proper motion and expansion. At the moment, the most viable explanation for its nature appears to be a micro-quasar (Muxlow et al. 2010; Joseph et al. 2011) displaying a high ratio of radio to X-ray luminosity. For instance, the source Cygnus X-3, which is one of the strongest Galactic micro-quasars, has a radio luminosity exceeding its X-ray luminosity by an order of magnitude (Nipoti et al. 2005). Thus a similar scenario could also be plausible in the case of the 43.78+59.3 transient.

In this paper we present photometric and spectroscopic observations of SN 2004am which despite its small distance has remained unstudied due to the high line-of-sight dust extinction and the fact it occurred coincident with the nuclear SSC M 82-L. We make use of this coincidence to infer an initial mass for the progenitor. We use deep, high spatial-resolution imaging from Gemini-N to search for NIR counterparts of SN 2008iz and the 43.78+59.3 transient and make use of these to investigate their nature and the line-of-sight extinctions towards these sources. Finally, we discuss the nature of the radio transients in M 82 making use of existing radio observations and compare these with the expectations from the SN rate estimates.

2 SN 2004am: OBSERVATIONS AND RESULTS

2.1 Observations and data reduction

SN 2004am was observed with the NIR imager and spectrograph LIRIS on the William Herschel Telescope (WHT). LIRIS spectra covering zJ bands were obtained on two epochs, 6 March and 25 November 2004. The observations included in this study are listed in Table 1. The NIR imaging data were reduced using standard IRAF routines and the spectroscopy using the FIGARO package as a part of the STARLINK software. SN 2004am appears coincident with the SSC M 82-L in these images (with seeing FWHM ∼ 1.5′′), and therefore, all the photometry was performed on subtracted images. The ISIS2.2 package (Alard & Lupton 1998) was used to convolve the better seeing image to the poorer seeing one, and to match the intensities and background prior to the image subtraction. The 25 Nov. 2004 observations of SN 2004am which despite its small distance could also be plausible in the case of the 43.78+59.3 transient.

In addition, we recovered optical images containing the site of SN 2004am from the Hubble Space Telescope (HST) archive. The pipeline-reduced products from the HST archive were used. SN 2004am was observed with the Advanced Camera for Surveys (ACS) HRC instrument in F555W and F814W filters on 5 July 2004 (SNAP 10272; PI: A. Filippenko). The site of SN 2004am was covered also with...
therefore we could not make use of it for reliable photometry.

SN 2004am was saturated in the image from 9 Feb 2004 and (PID 9788; PI: L.C. Ho) and 27 March 2006. Unfortunately, the ACS WFC instrument in F814W filter on 9 Feb. 2004 the LIRIS images using the aperture photometry procedure in Photometry of SN 2004am was performed in the subtracted 2.2 Photometry of SN 2004am

SN 2004am had already faded below the detection limit of M 82-L in the difference images and we conclude that However, no significant source was detected at the location of M 82-L in the difference images and we conclude that SN 2004am had already faded below the detection limit of the LIRIS field of view were used for the photometric calibration. The average of the zeropoint magnitudes obtained from 2MASS for three bright field stars covered in Instrument/Reference

| Date (UT) | Epoch (days) | V unfilt | I | J | H | K |
|-----------|--------------|---------|---|---|---|---|
| Nov. 21.5 | 14           | - 16.0  | - | - | - | - |
| Nov. 23.5 | 16           | - 16.1  | - | - | - | - |
| Dec. 28.4 | 51           | - 16.3  | - | - | - | - |
| Jan. 2.5  | 56           | - 16.4  | - | - | - | - |
| Jan. 17.4 | 71           | - 16.4  | - | - | - | - |
| Jan. 21.4 | 75           | - 16.4  | - | - | - | - |
| Jan. 30.3 | 84           | - 16.4  | - | - | - | - |
| Feb. 5.3  | 90           | - 16.4  | - | - | - | - |
| Mar. 5.2  | 118          | - 17.0  | - | - | - | - |
| Mar. 6.9  | 120          | - -     | 12.95±0.08 | 12.49±0.16 | 12.03±0.14 |
| June 5.9  | 211          | - -     | - | - | 13.06±0.12 |
| July 5.3  | 241          | - >20.3 | - | - |
| Nov. 25.2 | 384          | - -     | und. | und. | und. |

SN 2004am was saturated in the image from 9 Feb 2004 and therefore we could not make use of it for reliable photometry. However, we were still able to use it for precise relative astrometry of SN 2004am (see Fig. 1). We attempted to detect SN 2004am in the ACS/HRC images using images obtained with the same instrument and filters on 7 June 2002 as reference for the image subtraction with the ISIS2.2 package. However, no significant source was detected at the location of M 82-L in the difference images and we conclude that SN 2004am had already faded below the detection limit of HST by the 5 July 2004 epoch of observation (see Fig. 2).

2.2 Photometry of SN 2004am

Photometry of SN 2004am was performed in the subtracted LIRIS images using the aperture photometry procedure in the GAIA image analysis tool (Draper 2004). The JHK magnitudes from 2MASS for three bright field stars covered in the LIRIS field of view were used for the photometric calibration. The average of the zeropoint magnitudes obtained was adopted for the calibration and their standard deviation as the photometric uncertainty. The statistical uncertainty in the photometry as estimated by GAIA was in all cases negligible.

The residual noise from the flux of M 82-L leaves no obvious point source in the subtracted HST/ACS HRC images from 5 July 2004 (see Fig. 2). Aperture photometry was performed on the residuals using GAIA. For this we used a 0.25" radius aperture and a sky annulus between 1.5 and 2.0 × the aperture radius. No suitable point sources were present within the ACS/HRC field of view and thus we adopted an aperture correction from 0.25" to infinite aperture from Sirianni et al. (2005). Application of the appropriate Vegamag zeroptield yieldd m(F814W) = 20.3, which we adopt as an upper limit for the brightness of SN 2004am at this epoch.

2.3 The type and extinction of SN 2004am

The spectra of SN 2004am at both epochs are contaminated by the SSC. We subtracted the high signal-to-noise spectrum of M 82-L (provided by Lançon et al. 2008) from both epochs. This spectrum was manually scaled and the simple subtraction procedure resulted in an apparently flat spectrum with the SSC continuum removed in the first epoch (6th March 2004). However the subtraction from the second epoch left no identifiable SN features and we conclude that SN 2004am had faded below the detection limit of the spectral signal.

In Figure 3, the subtracted SN 2004am spectrum is compared to the spectra of three type II-P SNe: 2004et (Maguire et al. 2010), 1995V (Fassia et al. 1998) and 1997D (Benetti et al. 2001). All spectra were dereddened (by the values quoted in the original publications) and scaled to the continuum level at 1.3μm of SN 2004am. SN 2004am was dereddened with A_V = 3.7 and R = 2.4 as found for M 82-L by Lançon et al. (2008). SN 2004am has a similar spectrum to SNe II-P at the end of the plateau phase. The ejecta velocity from the P-Cygni troughs in the metal lines (e.g. Sr ii, Fe ii, and C i) indicates that SN 2004am appears more similar to the low velocity and low luminosity SN 1997D, than the other two. Cross-correlation and fitting Gaussians to the centroids of the sharpest P-Cygni profiles show that the velocity difference between SNe 2004am and 1997D is negligible, while the line troughs of SNe 1995V and 2004et are blueshifted by 1000 ± 500 km s^{-1}. Furthermore the spectral features of SNe 1995V and 2004et are visually broader (see Fig. 3).

The classification of SN 2004am as a type II-P is supported by its unfiltered light curve shown in Fig. 3, compared with the R-band light curves of two different II-P events: SNe 1999em and 2005cs (Elmhamdi et al. 2003; Pastorello et al. 2009). The plateau points of SN 2004am are unfiltered CCD magnitudes from Singer, Pugh & Li (2004), and the upper limit at 241 days has been estimated from the F814W HST images. The light curves of the two supernovae have been scaled to the same distance as SN 2004am, and have been dimmed to correspond to host galaxy extinctions.
of $A_R = 5.4$ and 4.2 mag, respectively. For this we adopted a
distance of 11.7 Mpc for the host galaxy of SN 1999em based
on Cepheids (Leonard et al. 2003) and 8.4 Mpc for the host
galaxy of SN 2005cs based on the application of the Ex-

danding Photosphere Method for SNe 2005cs and 2011dh in

the same host galaxy (Vinkó et al. 2012). The total (host
galaxy + Galactic) extinctions of $A_V = 0.31$ and 0.43 were
adopted for SN 1999em and 2005cs, respectively, following
Smartt et al. (2009) and a Galactic extinction of $A_V = 0.53$
(Schlegel et al. 1998) towards M 82. Assuming an epoch of
explosion of 14 days before the SN was first observed by
the LOSS was found to yield a good match with the post-
plateau drop in the light curves of SNe 1999em and 2005cs.
If the extinction toward SN 2004am is similar to that found
for M 82-L by Lançon et al. (2008) then its absolute magni-

ditude is fainter than that of the low-luminosity type II-P
SN 2005cs. SN 2004am is only likely to be a normal type
II-P SN if the extinction is higher than $A_R \approx 5$. Also, the

spectrum analysis indicates that SN 2004am has a low ejecta
velocity and is similar to SNe 1997D and 2005cs. Furthermore,
SN 2004am is not visible in the late deep image from
HST ACS at 241 days, allowing a conservative detection
limit of $I \approx 20.3$ to be set. The corresponding $R$-band limit

would be fainter than this due to the red $R - I$ colour of SNe

II-P at such epochs and the likely high extinction towards

SN 2004am. Figure 3 shows this is too faint to be compatible
with the nebular phase of SN 1999em, but is compatible with
a SN that ejected a low amount of $^{56}$Ni such as SN 2005cs
(Pastorello et al. 2009).

Comparison of the unfiltered SN photometry from
Singer, Pugh & Li (2004) on 5 March with our $K$-band pho-
tometry on 7 March yields a SN color of $(m_{CCD} - K) \approx +5.0$.
Typical $R - K$ magnitudes around 100 days for II-P SNe are
in the range $0.8 - 1.6$ (Maguire et al. 2010), hence this sup-
ports a host galaxy extinction of around $A_V \approx 4 - 5$. The
NIR colours $J - K = 0.9 \pm 0.2$ and $H - K = 0.5 \pm 0.2$
also support a large extinction for SN 2004am. Given the
evidence that low-luminosity SNe show a large NIR excess
which changes rapidly at around 100 days (Pastorello et al.
2009), the $JHK$ colours are compatible with extinctions in
the range $A_V \approx 3 - 6$.

### 2.4 Super-star cluster M 82-L and the progenitor
of SN 2004am

The HST/ACS WFC F814W ($I$-band) image (0.05 arcsec
pixel$^{-1}$) of M 82 obtained on 2006 March 27 was aligned
with the HST/ACS WFC F814W image from 2004 February
9. We measured the centroid positions for 30 point-like
sources visible in both the images using the IRAF APPHOT
package. A general geometric transformation function was
derived for the pairs of coordinates using the IRAF GE-
OMAP task. The astrometric uncertainty was estimated
from the RMS of the residuals from fitting the transforma-
tion function to the data points. The uncertainties in both
$x$ and $y$ estimated this way were about 4 milliarcsec (mas).

To measure the position of SN 2004am we first sub-
tracted the aligned 2006 image from the 2004 image using the
ISIS2.2 package. This revealed SN 2004am as a positive
saturated point-source at the location of M 82-L. To mini-
mise the biasing effects of the saturation, the position of the
supernova was measured in the subtracted image making

Table 2. Reported coordinates of the transients in M 82 discussed in this paper. All coordinates are J2000.

| Transient     | RA       | Dec      | Reference          |
|--------------|----------|----------|-------------------|
| SN 2004am    | 9:55:46.61 | +69:40:38.1 | Singer et al. (2004) |
| SN 2008iz    | 9:55:51.55 | +69:40:45.792 | Bruntmatter et al. (2009) |
| 43.78+59.3 transient | 9:55:52.5083 | +69:40:45.420 | Muxlow et al. (2009) |

![Figure 1](https://example.com/figure1.png)

**Figure 1.** $10'' \times 10''$ sections of ACS/F814W images (North is Up and East to the Left) showing the SSCs M 82-L (in the middle) and M 82-F (to the north-east from the centre) obtained on 9 February 2004 (left) and 27 March 2006 (middle) and the subtraction between the two obtained using ISIS2.2 (right). The images are shown with inverted intensity scale and the first two with log scaling. A positive saturated image subtraction residual is visible in the subtracted image at the location of M 82-L.
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3 SN 2008iz and the 43.78+59.3 Transient - Observations and Results

3.1 Observations and data reduction

The sites of SN 2008iz and the 43.78+59.3 transient were immediately visible at their positions from the radio observations (Fraser et al. 2009), we attempted to perform image subtraction to identify any faint transient source or low level variability at the site of either transient. We obtained pre-explosion observations from HST+NICMOS via MAST to use as reference images for the image subtraction. For SN 2008iz, the images used were a 448s exposure with the NIC2 camera (pixel scale 0.075′′/pix) in the F222M filter and a 1408s exposure in the F237M filter obtained using the same camera. For the 43.78+59.3 transient, the templates used were a 448s exposure in F222M and a 1408s exposure in F237M. All the NICMOS images were taken on 1998 April 12; the pipeline-reduced products from the HST archive were used.

3.2 Alignment and SN identification

As the field of view of both the NIRI (51′′ × 51′′) and NICMOS (19′′ × 19′′) images are small compared to the angular size of M 82, we employed a bootstrap technique to obtain accurate astrometry for our data. We first identified SDSS sources in an F814W-filter HST ACS mosaic (Mutchler et
al. 2007) of M 82, which allowed us to calibrate the world coordinate system (WCS) of this image to a high degree of accuracy, and subsequently used this frame as an astrometric reference for all other images.

The ACS mosaic of M 82 was downloaded from the HST MAST high level science products webpage\(^4\). This mosaic image has been corrected for the geometric distortion of ACS, and its internal astrometric accuracy is extremely good, with residuals in the alignment of the input tiles to the mosaic of ~0.1 pixels, corresponding to 5 mas. We identified 51 point sources which are in the Sloan catalog celestial coordinates, we re-fitted the WCS for the ACS mosaic using IRAF CCMAP and CCSETWCS. A general transformation was allowed, consisting of translation, rotation, scaling and a polynomial term. Three sources were discarded at this stage as outliers. The rms error in fitting the new WCS was 48 and 41 mas in R.A. and Dec., respectively.

Next, we identified 26 sources in common between our NIRI K-band image and the ACS F814W-filter mosaic. We measured the pixel coordinates of these as before with IRAF PHOT, and fitted the matched coordinate list with a general transformation using IRAF GEOMAP and GEOXYTRAN. We rejected two sources as clear outliers from the fit. The rms error in the fit was 20 and 22 mas in R.A. and Dec., respectively. The NIRI image was transformed to match the ACS image, and the two frames compared by eye to verify the transformation.

Using the Sloan-calibrated WCS, and using the values of R.A. and Dec. from radio observations given in Table 2, we identified the pixel coordinates of SN 2008iz and the 43.78+59.3 transient in the ACS image. These coordinates were then transformed to the NIRI image using the transformation determined previously with the GEOXYTRAN task.

Unfortunately, the site of SN 2008iz and the 43.78+59.3 transient are on different NICMOS images, and so each had to be aligned to the NIRI image separately. In each case, we matched between ten and twenty common sources, and transformed the NICMOS image to the pixel coordinates of the NIRI image using IRAF GEOMAP and GEOXYTRAN.

For SN 2008iz, we used the ISIS2.2 package to convolve the F222M- and F237M-filter NICMOS images to match the PSF and flux level of the NIRI K-band image. We then subtracted the convolved F222M and F237M images from the K image, and searched for residual flux at the site of the radio SN. As an additional test we subtracted the F222M image from the F237M image to see if a colour difference could produce a source.

The results of these subtractions are shown in Figures 5 and 6. As can be seen, there is a clear detection of a source co-incident with the radio coordinates of SN 2008iz in the subtractions between the NIRI and NICMOS images. The source in the difference image consists of positive flux, implying a brightening since April 1998. The source is closest in the subtraction between NIRI K and NICMOS F222M images (which is unsurprising given the good match between the bandpasses of the filters, as shown in Figure 7), although it is still significant in the F237 filter. No source is detected at the site of the SN in the subtraction between the F222M and F237M filters, indicating that there is not a point source with a large F222M – F237M colour at this location that could account for the source in the other subtractions.

We repeated the same procedure for the 43.78+59.3 transient, again finding a source at the radio position of the transient in the difference image. As the detection was not as clear as in the case of SN 2008iz, we repeated the convolution and subtraction process using HOTPANTS\(^5\) but obtained the same result.

We measured the pixel coordinates of both sources in the difference images obtained with ISIS and the F222M template image using the optimal filter centering algorithm in IRAF PHOT. In the case of SN 2008iz, we find an offset of 0.68 pixels (34 mas) between the expected and measured position of the transient, while for the 43.78+59.3 transient there is a 1.62 pixel (81 mas) offset. While this is slightly outside the combined rms error of the alignment (70 mas), we

\(^4\) http://archive.stsci.edu/prepds/m82/

\(^5\) http://www.astro.washington.edu/users/becker/hotpants.html
Figure 3. **Left-Top**: A comparison of the SN 2004am zJ spectra obtained on 2004 Mar 6 (black) with the spectrum of SSC M 82-L from Lançon et al. (2008) shown in red (along with a Gaussian smoothed spectrum overlaid in green). The pre-discovery spectrum of M 82-L was scaled and subtracted from the 2004 Mar 6 spectrum to leave a clean spectrum of SN 2004am. The major features are marked at the positions of the probable P-Cygni absorption troughs. **Left-Lower**: A comparison of the SN 2004am zJ spectrum with that of three other well studied II-P SNe near the end of the plateau phase. All spectra were dereddened and scaled to match the flux of SN 2004am at 1.3 \( \mu m \) (see text). As the spectra were taken with a diversity of resolutions, all were broadened (with a Gaussian FWHM of 40Å) and rebinned (to 20 ÅPixel\(^{-1}\)) to the lowest resolution for a meaningful comparison. The SN 2004am spectrum was dereddened with \( A_v = 3.7 \) and \( R = 2.4 \) as found for M 82-L by Lançon et al. (2008). **Right**: The light curve of SN 2004am compared with the R-band light curves of two type II-P SNe. The comparison light curves were scaled to a distance of 3.3 Mpc and dimmed to correspond to host galaxy extinctions of \( A_R = 5.4 \) and 4.2 for SN 1999em and 2005cs, respectively. The plateau points are unfiltered CCD magnitudes from Singer, Pugh & Li (2004), and the upper limit at 241 days is an estimated limit from the F814W HST image. An epoch of explosion of 14 days before the first observations by LOSS was adopted for SN 2004am to yield a good match with the post-plateau drop in the light curves of SNe 1999em and 2005cs.

3.3 Photometry of SN 2008iz and the 43.78+59.3 transient

For SN 2008iz and the 43.78+59.3 transient, we performed both PSF-fitting and aperture photometry in the \( K-F222M \) difference images. To set the zero point for the photometry, we measured the most isolated and point-like SSCs 6, c, d, F and L in the NIRI frame, adopting their \( F222M \) magnitudes from McCrady et al. (2003). As no bright enough individual stars were covered within the NIRI field of view, also the PSF was determined using the SSCs. According to McCrady et al. (2003) these SSCs have their projected half-light radii less than \( \sim 0.09\)”, i.e., are unresolved in our NIRI images with spatial resolution of FWHM \( \sim 0.2\)” and are within \( \sim 30\)” from SN 2008iz and the 43.78+59.3 transient. The average value and the standard deviation of the zeropoints obtained with the different clusters were adopted to be used for the photometric calibration and its associated uncertainty. We also attempted to use 2MASS sources in the NIRI field of view to set the zeropoint, but unfortunately there was an insufficient number of isolated sources with reliable 2MASS \( K \)-band magnitudes covered by the field of view. As a consistency check, photometry was also obtained from a subtracted image where the NIRI frame was scaled nonetheless consider the association convincing given that the transient source is detected at a relatively low signal to noise. We identified nine other point sources which appeared in a 12”x12” region in the difference image for the 43.78+59.3 transient; from this we calculate a probability of a variable or transient source coincident to less than 81 mas as \( \sim 0.1\) per cent.
to match the flux units of the NICMOS template prior to the subtraction. Using the PHOTFLAM value in the FITS header of the latter yielded a $K$ magnitude for SN 2008iz within $\sim 0.1$ mag from the one obtained using the SSCs.

Using PSF fitting for SN 2008iz gives a magnitude of $F'_{222}M (\sim K) = 15.91 \pm 0.16$ where the error is dominated by the uncertainty in the zeropoint magnitude ($\pm 0.14$ mag). The photometric uncertainty was estimated via PSF-fitting to artificial sources placed close to the SN position after subtracting the PSF-fit at the SN position. For comparison, using a photometric aperture with an 8 pixel radius for SN 2008iz gives a magnitude of 16.03. In this case the zero-point was obtained using aperture photometry (8 pixel radius) of the five SSCs. Varying the photometric aperture by a few pixels causes the photometry of SN 2008iz to vary by up to 0.2 mag. The measured magnitude is also dependent on the region used to measure the sky background at the SN location. The convolution used in the image subtraction will also affect the noise properties of the subtracted image. For these reasons, we adopt a conservative error of $\pm 0.3$ mag for our aperture photometry which is larger than would be implied by Poissonian statistics.

For the 43.78+59.3 transient we obtain a magnitude of $F'_{222}M = 17.87 \pm 0.28$ by PSF fitting. For the aperture photometry we used a smaller aperture with a 4 pixel radius to avoid including flux from an image artifact to the south of the transient in the difference image (as can be seen in Fig. 4(c)). Using the zeropoint from aperture photometry (4 pixel radius) of the five SSCs, we find a magnitude of $F'_{222}M = 17.59$, with the same conservative error of $\pm 0.3$ mag as estimated for SN 2008iz. As a check on the effect of the small aperture on our photometry, we used the same 4 pixel radius to measure the magnitude of SN 2008iz, and found a value which differs only by 0.2 mag from that found through the 8 pixel aperture. As this difference is smaller than our errors, we do not regard this as a significant source of error.

From now on we adopt the PSF fitting based magnitudes as the most accurate ones to be used in this study. We note that these are also consistent with the magnitudes obtained through aperture photometry but have smaller uncertainties. As a final test we used SYNPHOT to calculate the $F'_{222}M - K$ colour of a range of black bodies between 100 and 50 000 K. For temperatures hotter than 500 K, we find that the colour difference between the two filters is negligible (0.02 mag or less). While the difference does become large (>0.1 mag) for T < 400 K, if the flux in SN 2008iz was coming from dust at this temperature, then it would be emitting in the mid-IR rather than the $K$ band (Mattila et al. 2008a).

## 4 DISCUSSION

### 4.1 SN 2004am

SN 2004am is the only SN ever discovered at optical/IR wavelengths in the prototypical starburst galaxy M 82. It occurred spatially coincident with the obscured SSC M 82-L and suffers from a host galaxy extinction of $A_V \simeq 5 \pm 1$ which is consistent with the extinction derived for M 82-L. From the compiled photometry and our NIR spectra it is clearly a type II-P SN, which one would expect to come from a red supergiant progenitor star. It is likely a low luminosity type II-P SN and these have been proposed to come from stars.
toward the lower mass range that will produce core-collapse (Smartt et al. 2009).

Lançon et al. (2008) and McCrady & Graham (2007) show that the NIR spectra of M 82-L are dominated by the spectral features of red supergiant stars. The virial mass of the cluster is estimated to be $4 \pm 0.6 \times 10^6 M_\odot$ (McCrady & Graham 2007) which agrees with the mass estimate from the cluster luminosity by Lançon et al. (2008). Assuming the best fit age of around 18 Myr (Sect. 2.4) for M 82-L, the single stellar population models of Lançon et al. (2008) suggest there are likely to be of the order of 100-260 red supergiants in the cluster, depending on the initial mass function and lower mass limit used. Clearly there is a rich population of red supergiants as potential progenitors of type II-P SNe.

In fact M 82-L is the most massive host cluster of a SN that has been accurately measured in the nearby Universe. Nearby SNe do not tend to be discovered coincident with the most massive unresolved clusters. In the volume limited sample of 20 II-P SNe reviewed by Smartt et al. (2009) which have high-resolution pre-explosion images available, only two fall on compact clusters. This may be a little surprising, however Pellerin et al. (2007) show that in NGC 1313 75-90 per cent of the UV flux is produced by stars outside the dense clusters. They propose that the late O and early B-type stars (that will eventually produce 8-30 $M_\odot$ red supergiants) are diffusely spread throughout a galaxy due

Figure 5. Gemini post- and HST pre-explosion images of the site of SN 2008iz, together with difference images obtained with isis. In all cases the images are centred on the radio coordinates of the transient, with North up and East left. All images are $3'' \times 3''$. 

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Figure 6. Gemini post- and HST pre-explosion images of the site of the 43.78+59.3 transient, together with difference images obtained using ISIS and hotpants. In all cases the images are centred on the radio coordinates of the transient, with North up and East left. All images are 3″ × 3″.

to infant mortality of stellar clusters (Lada & Lada 2003). Crockett et al. (2008) have shown that the type Ic SN 2007gr exploded on the edge of a bright object in NGC 1058 and suggested that this may be a host cluster. This is one of 12 type Ib/c SNe studied by Eldridge et al. (2013) at high resolution and is the only one possibly associated with a stellar cluster, again supporting an approximate figure of 10 per cent.

The mass range that we suggest is appropriate for the progenitor (12$^{+7}_{-3}$ M$_\odot$) is in agreement with the masses of red supergiants directly detected in nearby galaxies. Smartt et al. (2009) present a full list of a volume and time limited search for SN progenitors, and find the likely progenitor population of II-P SNe are red supergiants of initial masses 8-17 M$_\odot$. The mass of the progenitor of SN 2004am is consistent with this mass range. The fact that it was in a cluster with such a rich red supergiant population further supports the idea that this stellar evolutionary phase directly gives rise to hydrogen rich II-P SNe. However, we note that Fraser et al. (2011) suggest a lower mass range of between 8-9 M$_\odot$ for the progenitors of sub-luminous Type II-P SNe, and if SN 2004am was one of these events, it is also in agreement with the expected progenitor mass range within the 1σ uncertainty.

4.2 SN 2008iz

In Fig. 8 we compare the radio luminosities of SN 2008iz and the two radio transients in M 82 (41.5+59.7 and 40.59+55.8) of unknown nature with the peak spectral radio luminosi-
ties of SNe with different types. The luminosities of the two transients are comparable with those of type II-P SNe, such as SNe 1999em and 2004dj. The peak luminosity and time to reach the peak make SN 2008iz very similar to the well observed type IIb SN 1993J, thus suggesting that also their progenitor stars might be similar. However, the expansion velocity of ~20 000 km s\(^{-1}\) observed for SN 2008iz (Brunthaler et al. 2010) was somewhat higher than the one for SN 1993J (~15 000 km s\(^{-1}\); Marcaide et al. 1995).

At a distance of 3.3 Mpc, SN 2008iz has an absolute magnitude of K = -11.68 ±0.16 for zero host galaxy extinction. The first detection of SN 2008iz at radio wavelengths was in March 2008, with a best estimate for the explosion epoch of 2008 Feb. 18, implying that at the time of our NIRI observation the SN was already ~480 days old. Unfortunately there are few SNe with NIR light curves for comparison at this late phase. However, SN 1987A had an absolute magnitude of K = -12.2 (Suntzeff & Bouchet 1990) at ~450 days, while at 300 days SN 2004et had an absolute magnitude of K = -13.35 (Maguire et al. 2010). These magnitudes are comparable to that of SN 2008iz with a modest amount of extinction (A\(_K\) ≤ ~1 mag).

Brunthaler et al. (2010) estimated the extinction towards SN 2008iz to be A\(_V\) = 24.4 mag, using the intensity of the 12\(^{12}\)CO (J = 2 \rightarrow 1) line from Weiß et al. (2001), together with the CO to H\(_2\) ratio and the relation of Giaver & Ozel (2009) between hydrogen column density and extinction. We find however, that when using the same data and relations as Brunthaler et al. (2010), we obtain a total extinction of A\(_V\) = 48.9 mag. This is exactly twice the value found by Brunthaler et al. (2010), and we suggest that these authors may have neglected to multiply the value of N(H\(_2\)) by two to convert to hydrogen nuclei before applying the hydrogen nuclei to extinction relation of Giaver & Ozel (2009).

A\(_V\) = 48.9 mag implies an extinction in K of ~5.5 mag (Cardelli, Clayton, & Mathis 1989). Such a high extinction would put SN 2008iz at an absolute magnitude of K ~ -17 mag, which is uncomfortably high for a SN at such a late phase. While a late-time near-infrared excess has been observed for several SNe, and attributed to dust formation in

Figure 7. Transmission curves for HST (telescope + instrument + filter) and Gemini (filter only) used for the pre- and post-explosion imaging of SN 2008iz and the 43.78+59.3 transient.

Figure 8. Peak spectral radio luminosity versus time to reach the peak (normalized to 5 GHz) for different types of CCSNe. The four M 82 transients have been added to allow comparison with historic radio SNe. SN 2008iz is represented by a cross, whereas the rest of the transients, for which the peak epoch is unknown, are represented as dash-dotted (41.5+59.7), dotted (40.59+55.8) and dashed (43.78+59.3) lines. The gray region represents the range that the galactic microquasar Cygnus X-3 has been observed to reach in major flare states at radio wavelengths (Waltman et al. 1995).

4.3 The 43.78+59.3 transient

One of the possible explanations advocated for the 43.78+59.3 transient by Muxlow et al. (2010) and Joseph et al. (2011) was that it was an extra-galactic microquasar. Microquasars are the stellar analogs to quasars, and are believed to arise from a compact object accreting matter from a stellar companion, and in the process forming a relativistic jet. They typically display strong and variable radio and X-ray emission. In Figure 8 we compare the radio luminosity of the 43.78+59.3 transient with the range of luminosities that the Galactic microquasar...
Cygns X-3 has been observed to reach in major flare states (Waltman et al. 1995). Only if Cygns X-3 would increase its highest observed radio luminosity by a factor of ~10, the 43.78+59.3 transient would be comparable in brightness. We note that recently Batejat et al. (2012) have proposed that three rapidly variable radio sources within the nuclear regions of the ultraluminous infrared galaxy Arp 220 having their radio luminosities a factor ~100 times larger than the luminosity of the 43.78+59.3 transient could be associated with highly beamed microquasars. The apparent magnitude of the 43.78+59.3 transient is K ~ 17.9, corresponding to an absolute magnitude of K ~ -9.7 if assuming no host galaxy extinction. Such a bright absolute magnitude would make the 43.78+59.3 transient the brightest known example of a microquasar by quite some margin; for comparison, the Galactic micro quasar SS433 has an absolute magnitude which varies between K = -5.7 and K = -6.4 (Kodaira, Nakada & Backman 1985; Blundell & Bowler 2004).

The 43.78+59.3 transient was first detected in the radio 40 days prior to the epoch of the Gemini image. From the templates presented in Mattila & Meikle (2001) at +40 days, we would expect a normal, unextinguished SN in M 82 to have an apparent magnitude of K ~ 9.6. Clearly the observed magnitude of the 43.78+59.3 transient appears difficult to reconcile with a SN. If, however, the first detection of the 43.78+59.3 transient did not mark the explosion epoch, but was instead late time radio emission, then the faint absolute magnitude is less puzzling. Similarly, ~70 magnitudes of extinction in V would bring the observed and expected K magnitudes into agreement. However, even with a high extinction or an earlier explosion epoch, its observed radio flux density evolution (Gendre et al. 2012; Rob Beswick, private communication) points to a non-SN origin for this source.

The absolute magnitude of the 43.78+59.3 transient is comparable to the quiescent magnitude of Luminous Blue Variables (LBV). LBV eruptions, also termed “supernova impostors” (Van Dyk et al. 2000) can reach an absolute magnitude of ~ -12 to -16 in V. The SN impostors SN 2009ip and UGC 2773 OT2009-1 have upper limits on their 8 GHz radio luminosity of < 1.3 x 10^26 erg s^{-1} Hz^{-1} and < 2.6 x 10^26 erg s^{-1} Hz^{-1} respectively (Foley et al. 2011). These limits are an order of magnitude higher than the peak radio luminosity of the 43.78+59.3 transient, and hence the luminosity of the latter is not inconsistent with the limited information on the properties of SN impostors at radio wavelengths.

The NIR magnitude of the 43.78+59.3 transient is also reminiscent to that of a nova at peak. Most common novae fade rapidly after outburst, but from the template light curves presented in Stoppe et al. (2010) either an F or D-class nova could still be bright at ~+40 days. However, classical novae are usually unusual strong radio sources, and the peak of the radio light curve tends to be later than the optical maximum, hence the MERLIN detection would appear incongruous with this scenario.

The nature of the 43.78+59.3 transient remains elusive, and on the basis of the limited data available, we regard an extremely bright extragalactic microquasar as the most plausible scenario, perhaps from a high-mass X-ray binary such as LS 5039 (Clark et al. 2001), but with a high ratio of radio to X-ray flux. A bright extragalactic microquasar was proposed as the most likely explanation by Muxlow et al. (2010) and Joseph et al. (2011). We concur with that conclusion although it would mean that the NIR luminosity is a factor of about 30 higher than Galactic microquasars.

### 4.4 Comparison with the expected SN rate

SNe 2004am and 2008iz are still the only supernovae detected at optical/NIR wavelengths in M 82. This is perhaps somewhat surprising given the SN rate estimates of around 7-9 per century (Fenech et al. 2008; Fenech et al. 2010), the small distance and the appeal of this galaxy as a target in SN searches. It is very likely that extinction has hampered the discovery of recent SNe in the past decade (for estimates of extinctions towards the radio SNRs of M 82 see Mattila & Meikle 2001). Over the last ~20-30 years during which M 82 has been regularly monitored at radio wavelengths, the detection of two confirmed SNe (SNe 2004am and 2008iz) and the two radio transients (41.5+59.7 and 40.59+55.8) with a possible SN origin is in reasonable agreement with the expectation. However, the discoveries of SNe 2004am and 2008iz have important lessons for attempts to find heavily extinguished SNe in more distant starburst galaxies. While SN 2008iz was recovered at a comparable magnitude to the two SNe found by Kankare et al. (2012) in their NIR LIRG SN search, it is of note that Fraser et al. (2009) originally reported a non-detection for both SN 2008iz and the 43.78+59.3 transient. We have only recovered these transients with a careful analysis using a posteriori knowledge of the source positions from radio observations. Without these data, it is likely that SN 2008iz would have remained undiscovered in the NIR.

Recently Mattila et al. (2012) studied the fraction of CCSNe missed by rest-frame optical SN searches and found an average local value of ~20% increasing to ~40% of CC-SNes missed at z ~1-2. These estimates highlight the need for a better control of the SN activity in the obscured environments such as the nuclear regions of nearby starburst galaxies and LIRGs. Unless properly accounted for such systematic effects can dominate the uncertainties in the CCSN rates at high redshift (e.g., Melinder et al. 2012; Dahlen et al. 2012).

### 5 CONCLUSIONS

SN 2004am was the first optically detected SN in M 82 when discovered by LOSS (Singer et al. 2004), and remains the only transient discovered in the optical. We show that it is most likely to have been a sub-luminous, highly redened Type II-P event coincident with the obscured nuclear SSC M 82-L. From the cluster age we inferred a progenitor mass of 12^{+7}_{-3} M_{\odot} which is within the uncertainties in agreement with the expected progenitor mass range for such events. Making use of high spatial-resolution K-band imaging we detected NIR counterparts for both SN 2008iz and the 43.78+59.3 transient previously detected only at radio wavelengths. Our late-time K-band magnitude rules-out an extremely high extinction towards SN 2008iz. The nature of the 43.78+59.3 transient still remains elusive, an extremely bright microquasar in M 82 being the most plausible scenario.
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