Diffraction-Limited Subaru Imaging of M 82: 
Sharp Mid-Infrared View of the Starburst Core*

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Abstract

We present new imaging at 12.81 and 11.7 $\mu$m of the central \( \sim 40'' \times 30'' \) \((\sim 0.7 \text{kpc} \times 0.5 \text{kpc})\) of the starburst galaxy M 82. The observations were carried out with the COMICS mid-infrared (mid-IR) imager on the 8.2 m Subaru Telescope, and are diffraction-limited at an angular resolution of <0.4. The images show extensive diffusive structures, including a 7$''$-long linear chimneylike feature and another resembling the edges of a ruptured bubble. This is the clearest view to date of the base of the kpc-scale dusty wind known in this galaxy. These structures do not trace back to a single central point, implying multiple ejection sites for the dust. In general, the distribution of dust probed in the mid-IR anticorrelates with the locations of massive star clusters that appear in the near-infrared. The 10--21 $\mu$m mid-IR emission, spatially integrated over the field of view, may be represented by hot dust with temperature of \( \sim 160 \text{ K} \). Most discrete sources are found to have extended morphologies. Several radio HII regions are identified for the first time in the mid-IR. The only potential radio supernova remnant to have a mid-IR counterpart is a source which has previously also been suggested to be a weak active galactic nucleus. This source has an X-ray counterpart in Chandra data which appears prominently above 3 keV and is best described as a hot \((\sim 2.6 \text{ keV})\) absorbed thermal plasma with a 6.7 keV Fe K emission line, in addition to a weaker and cooler thermal component. The mid-IR detection is consistent with the presence of strong [Ne II] 12.81 $\mu$m line emission. The broad-band source properties are complex, but the X-ray spectra do not support the active galactic nucleus hypothesis. We discuss possible interpretations regarding the nature of this source.

Key words: galaxies: individual (M 82) — galaxies: starburst — infrared: galaxies — techniques: high angular resolution

1. Introduction

The galaxy M 82 (NGC 3034) hosts the nearest and best example of an ongoing massive starburst, making it an excellent target for detailed studies at all wavelengths. The galaxy is thought to have undergone an interaction event with its neighbor M 81 \( \sim 10^8 \text{ yr} \) ago (Gottesman & Weliachew 1977), triggering a massive nuclear starburst \( \sim 5 \times 10^7 \text{ yr} \) ago (Rieke et al. 1980). There is also evidence for several other star-formation episodes, both older and younger (de Grijs et al. 2001; Förster Schreiber et al. 2003a). Around 40 supernova remnants (SNRs) have been identified in the core (Fenech et al. 2008), and one new supernova (SN) is produced every \( \sim 3 \text{ yr} \) (e.g., Rieke et al. 1980; Jones & Rodríguez-Espinosa 1984). The energy output of the super star clusters hosting the SNe is thermalized and drives a large scale superwind along the galactic minor axis (Heckman et al. 1990) which can be observed in detail because of the favorable edge-on inclination of the source.

In the infrared, M 82 has been extensively studied with all space missions. Its infrared luminosity is measured to be \( 5 \times 10^{10} \text{ L}_\odot \), and it shows prodigious dusty outflows containing polycyclic aromatic hydrocarbon (PAH) grains in...
the mid-infrared (mid-IR) extending on kpc-scales (e.g., Helou & Walker 1988; Sturm et al. 2000; Förster Schreiber et al. 2003b; Engelbracht et al. 2006; Kaneda et al. 2010; Roussel et al. 2010). There are very few high-spatial-resolution mid-IR studies of the core itself on scales of order 100 pc, because of size limitations of space missions. With their large primary mirrors, ground-based telescopes can achieve the best spatial resolution currently possible. In the \( N \) (8–13 \( \mu m \)) band atmospheric window, the highest resolution studies thus far are the works of Telesco and Gezari (1992, hereafter TG92) and Achtermann and Lacy (1995, hereafter AL95), with nominal resolutions of 1\(^{\prime}\)1 and 2\(^{\prime}\), respectively.

In this work, we present the first subarcsec mid-IR \( N \)-band images of the core of M82. The galaxy was observed as an extension of our recent work of Seyfert galaxies (Gandhi et al. 2009), as part of a study to understand the mid-IR emission of galaxies at high angular resolution. The observations were carried out at the 8.2 m Subaru Telescope. At wavelengths of 11.7 and 12.81 \( \mu m \), our imaging is diffraction-limited at \( < 0.04 \). These new images provide the sharpest mid-IR view of structures at the base of the superwind, and allow an extensive multiwavelength comparison of individual sources. Several \( \text{H}\alpha \) regions are identified in the mid-IR. We also discuss the nature of a putative active galactic nucleus candidate. Using a mid-IR detection and new Chandra data, we rule out the AGN hypothesis and discuss other possibilities, including supernova remnant ionization and emission from a starburst.

Distance estimates to M82 have ranged over 3.2–5.2 Mpc (e.g., Burbidge et al. 1964; Tully 1988; Sakai & Madore 1999). Some of the latest measurements suggest a distance at the lower end of this range based upon accurate determination of the tip of the red giant branch magnitude (Karachentsev et al. 2004; Dalcanton et al. 2009). We adopt a value of 3.53 Mpc herein, resulting in a physical scale of 17.1 pc per arcsec. Our imaging resolution limits correspond to \( \approx 6.1 \) pc at 11.7 \( \mu m \) and 6.7 \( \mu m \) at 12.8 \( \mu m \).

2. Observations

Observations were carried out at Subaru on the night starting 2009 May 4, under generally clear weather conditions. The source was observed at the beginning of the night close to meridian, i.e., near its maximum altitude of 40\(^{\circ}\). The Cooled Mid-Infrared Camera and Spectrometer, or COMICS (Kataza et al. 2000) was used in imaging mode with standard chopping and nodding off-source. Due to the extended nature of the emission from M82, a relatively large chop throw of 30\(^{\prime}\) was used so that the sky position lay completely outside a single field-of-view of the detector. Technical difficulties prevented us from using larger throws. A north–south chop direction was adopted, because this is approximately perpendicular to the apparent major axis of the galaxy. Integration times of 60 s were used at each chop position. Subsequently, the telescope was nodded to a position at an offset of 1\(^{\prime}\) to the north, and the above chopping series was replicated, this time entirely on sky.

The above sequence was repeated 10 times, resulting in a total on-source exposure of 600 s per filter and a total telescope time of \( \approx 50 \) min per filter after accounting for observing efficiency. Imaging was obtained in the NeII (narrow-band) and the N11.7 filters, with central wavelengths (and full widths at half maximum) of 12.81 (0.2) \( \mu m \) and 11.7 (1.0) \( \mu m \), respectively.\(^1\) The median airmasses of the source were 1.56 and 1.65, respectively.

The Cohen standard star PI2 UMa (HD 73108: Cohen et al. 1999) was observed for photometric calibration just before the target at an airmass of \( \approx 1.44 \). On-chip chopping with a throw of 10\(^{\prime}\) was used, and two nod observations were obtained with exposure time 10 s each. Seeing was measured in this observation, as well as in a standard star observation of HD 108381 (with identical observational setup to PI2 UMa; in the N11.7 filter only) carried out approximately 1 hr after the target observation was completed. The maximum systematic error in the photometry due to the absolute calibration of the standard star is \( \approx 3\% \), and this error is added quadratically to all target photometric errors.

3. Data Reduction

Data reduction was carried out using routines provided by the COMICS team (\texttt{qseries} package),\(^2\) and following the procedures recommended in the COMICS Data Reduction Manual v.2.1.1. Some additional image manipulation was carried out in IRAF.\(^3\) The COMICS data flow returns two sets of images for each observation: (1) a “COMA” cube of data frames including all images obtained in one observing block; (2) a single chop-subtracted “COMQ” image, coadded over all the frames in that block.

The recommended flat fielding procedure for imaging is a “self-sky-flat”, in which the “off” beam chop positions are used for flat fielding the “on” beam ones, and vice versa. This is possible because the detector is illuminated quite uniformly by sky background, much brighter than the imaged sources. To create these flats, dark frames were first subtracted from each cube of data. For the standard star reduction, the on- and off-chop beam data cubes were averaged to create a separate mean image for each of the two beams (hereafter, called “mean beam images”). Low spatial frequency trends across the detector are then removed by simply dividing through a heavily Gaussian-smoothed version of the mean beam images. This results in the desired flats for one observing block, and each COMQ coadded frame can be divided by these flats to create calibrated on- and off-beam standard star images, with the pixel-to-pixel sensitivity variation removed. This flat fielding procedure was carried out separately for each nod position, following which the two beams are shifted and averaged (with flux inversion of one).

The target was observed with a large chop angle so that the off-beam images are devoid of any bright sources. Hence, only the flats created from the off-beam positions are required to calibrate the on-beam target images. So, for the target, we simply divided each COMQ image by the off-beam flat created as described above. This was done identically for the nod position as well. Each flat fielded nod position image was then subtracted from its immediately preceding flat fielded target

\(^1\) [http://canadialир.isas.jaxa.jp/comics/open/guide/filter].
\(^2\) [http://www.naoj.org/Observing/DataReduction/].
\(^3\) [http://iraf.noao.edu/].
image, resulting in 10 calibrated and background-subtracted images of the target. One of the pointlike sources in each image was used as a reference for determining small shifts necessary to create the final coadded image.

Two systematic sources of noise affect COMICS observations. Firstly, a low level random noise in the form of horizontal stripes is introduced into every exposure by the readout amplifiers. Although it is largely periodic in nature across the field of view as a result of the 16 identical amplifier channels employed, this is difficult to remove because of (1) its random nature from exposure to exposure; and (2) the fact that our target covers most of the field of view, leaving free very little of the CCD for determination of the noise level. No optimal solution was found for removal of this read noise component without introducing additional statistical uncertainties in the process, so no attempt is made to remove it, except for display purpose.

Secondly, we find nonnegligible background residuals in our N11.7 image. This is a result of the fact that (1) the chop throw (and nod offset) is relatively large which means that the background and target optical light paths differ significantly; and (2) the typical time delay between a chopped beam observation and its corresponding nod observation is of order several minutes, during which time the sky level can vary significantly. These residuals are more prominent in the N11.7 image because the wide filter width could make it more sensitive to sky variations. In order to remove these, the final NeII image was rescaled in order to produce the best match to the target in the N11.7 filter, and then subtracted. This leaves a background image dominated by the N11.7 background residuals, with only some additional low level structures due to the varying SEDs of targets across the field of view between the two wavelengths. This background image can then be subtracted from the shifted and coadded N11.7 image to create the desired residual-free product.

Final calibrated images are shown in figure 1. The attached absolute astrometry was determined based on multiwavelength comparison of detected sources, as described in the following sections. The coordinates attached to all images presented herein are for the J2000.0 equinox.

4. Point Spread Function

The point-spread-function (PSF) size in our observations may be accurately measured from the photometric standard star observations, which were carried out both before and after the target observations. The stellar flux contours are displayed in figure 2. Also overplotted is the expected diffraction limit resolution for both filters. The 50% stellar flux contour matches the expected ideal full-width at half-maximum (FWHM), meaning that our observations were closely diffraction-limited at 0′.36 and 0′.39 in the N11.7 and NeII filters, respectively.

5. Source Detection and Photometry

In order to isolate the most significant discrete sources in the target field of view, we carried out automatic detection with the SExtractor package (Bertin & Arnouts 1996). The dominant source of uncertainty for source detection and photometry is the diffuse and bright galactic background emission. An iterative process of interpolating the image on a smooth mesh and removing detected sources is employed for proper modeling of this background. But the complex nature of the observed emission makes the local background quite sensitive to the choice of the mesh size. We thus decided to run SExtractor in two passes using different mesh sizes. In the first instance, a background map is created from a mesh with squares of 8 × 8 pixels. A limit of 3σ (with σ being the root-mean-square variance in the background map at the mesh location of interest) was chosen for defining significant sources, and a rather small minimum detection area of 3 contiguous pixels with a significant signal was adopted for detecting the more compact sources. In a second pass, we chose a smaller background mesh size of 4 × 4 pixels, and ran the source detection procedure again. SExtractor fits ellipse profiles to all sources, and only those sources whose centroids remained consistent to within some threshold between the two passes were retained in the end. A threshold of size equal to the semiminor axis for the NeII filter (and twice this value for the N11.7 images which are affected by worse residuals, as described above) was found by experimentation to work well.

Note that a very small background mesh can result in subtraction of some flux from the source wings themselves. Test runs on the photometric star images showed that using a mesh as small as 4 × 4 pixels results in fluxes lower than the total expected values by factors of ~1.2 and 1.3 (N11.7 and NeII, respectively), so all SExtractor-determined fluxes have been increased by these amounts. Because of the clumsy nature of the galaxy emission, additional systematic uncertainties of ~10% are estimated for this background correction, and these have also been included. A better photometric solution will require accurate mapping of the galactic background emission (in longer exposures or using space telescopes), which the present data do not allow.

Calibration of counts to flux was carried out using the photometric standard observations described in section 2. Final source fluxes are listed in table 1 and the sources are identified in figure 3.

Finally, in order to determine limiting fluxes for non detections, we simulated two dimensional Gaussian profiles matched to the PSF, scaled these according to flux and added them in at specific positions in the images where limits were required. We then passed these images through our detection pipeline, and determined the flux limit corresponding to the faintest source that could be detected. We find nominal point source flux limits of ~43 mJy in the NeII filter and ~18 mJy in the N11.7 at the radio kinematic center position of Weliachew, Fomalont, and Greisen (1984). But these limits can vary significantly with position and source morphology assumed, so we quote relevant numbers for some interesting sources individually in the following sections.

6. Multiwavelength Registration of Images

Registration of images at multiple wavelengths (to better than half-arcsec accuracy) is a nontrivial task, given the small field-of-view of COMICS, the extended nature of the bulk of the emission, and the strong dust extinction toward the core. Extensive high resolution radio studies over the years have
Fig. 1. COMICS images in the NeII filter (top) and N11.7 filter (bottom). The field of view displayed is 286 x 213 pixels wide which, at a pixel scale of 0.133, results in a field size of 38'' x 28''. The linear grayscale is in units of mJy pix⁻¹.
was identified in which four radio H II regions coincided with matches with our mid-IR NeII image. A possible solution of McDonald et al. (2002, hereafter M02) to search for source cross-registration. We used the VLA/MERLIN 5/15 GHz study regions, which arguably provide the best reference system for determining for the NeII filter, and all four H II regions are also determined for the NeII filter, and all four H II regions are also detected in the N11.7 image.

In order to check whether these mid-IR detections are consistent with H II region emission, we plot their radio to mid-IR spectral energy distributions (SEDs) in figure 4, and compare to the SEDs of the massive embedded star clusters identified by Galliano et al. (2008) in NGC 1365. The overall match is excellent given the long “lever arm” between the radio

accurately mapped many supernova remnants (SNRs) and H II regions, which arguably provide the best reference system for cross-registration. We used the VLA/MERLIN 5/15 GHz study of McDonald et al. (2002, hereafter M02) to search for source matches with our mid-IR NeII image. A possible solution was identified in which four radio H II regions coincided with mid-IR NeII detections to within 0.5. These four are listed in table 1 and are highlighted in figure 4. The rms error of the astrometric solution fit was 0.27 pixels, or 0.036, ~ 10 times smaller than a single resolution element. Adopting this solution required a shift of ~ 0.5 from the raw Subaru astrometry baseline. The astrometry for the N11.7 image was tied to that determined for the NeII filter, and all four H II regions are also detected in the N11.7 image.

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Table 1. Parameters of detected discrete sources.

| #  | Mid-IR designation | $F_{\text{NeII}}$ (mJy) | $F_{\text{N117}}$ (mJy) | Cross-ID and comments |
|----|-------------------|------------------------|------------------------|----------------------|
| 1  | J2000.0           | 148.05 ± 40.5          | 139.30 ± 54.0          | 110 ± 12             | 19 ± 3          | 39.29 ± 54.2 (M02) |
| 2  | J2000.0           | 148.69 ± 42.3          | 139.94 ± 55.9          | 95 ± 12              | —               | —                 |
| 3  | J2000.0           | 149.65 ± 45.2          | 140.91 ± 58.8          | 419 ± 44             | 80 ± 8          | 40.95 ± 58.8 (M02) |
| 4  | J2000.0           | 149.68 ± 43.0          | 140.93 ± 56.6          | 101 ± 11             | —               | —                 |
| 5  | J2000.0           | 149.92 ± 42.4          | 141.18 ± 56.0          | 338 ± 36             | 85 ± 9          | 41.17 ± 56.2 (M02); W2 faint (AL95) |
| 6  | J2000.0           | 150.24 ± 43.1          | 141.51 ± 56.7          | 771 ± 81             | 233 ± 24        | W2 bright (AL95) |
| 7  | J2000.0           | 150.42 ± 46.2          | 141.69 ± 59.8          | 212 ± 23             | —               | —                 |
| 8  | J2000.0           | 150.44 ± 48.2          | 141.70 ± 61.8          | 38 ± 4               | 27 ± 3          | weak NeII:N11.7 |
| 9  | J2000.0           | 150.75 ± 47.3          | 142.01 ± 60.9          | 72 ± 8               | —               | —                 |
| 10 | J2000.0           | 150.80 ± 44.9          | 142.06 ± 58.6          | 150 ± 16             | 64 ± 7          | 42.08 ± 58.4 (M02) |
| 11 | J2000.0           | 151.01 ± 45.7          | 142.28 ± 59.4          | 233 ± 25             | 129 ± 13        | W1 faint (AL95); tentative association with 42.21 ± 59.2 (M02) |
| 12 | J2000.0           | 151.44 ± 47.3          | 142.71 ± 61.0          | 321 ± 34             | 82 ± 9          | on “bridge” |
| 13 | J2000.0           | 151.44 ± 43.7          | 142.72 ± 57.3          | 707 ± 75             | 153 ± 16        | W1 bright (AL95) |
| 14 | J2000.0           | 151.53 ± 49.1          | 142.80 ± 62.7          | 69 ± 8               | —               | on “bridge” |
| 15 | J2000.0           | 152.11 ± 49.4          | 143.38 ± 63.1          | 559 ± 59             | 145 ± 15        | another component of W1 bright (AL95) |
| 16 | J2000.0           | 152.24 ± 47.5          | 143.52 ± 61.2          | 55 ± 8               | —               | —                 |
| 17 | J2000.0           | 152.50 ± 49.2          | 143.78 ± 62.9          | 465 ± 49             | 75 ± 8          | western limb of “bubble” (E1 of AL95) |
| 18 | J2000.0           | 152.70 ± 45.9          | 143.99 ± 59.6          | 42 ± 6               | —               | —                 |
| 19 | J2000.0           | 153.20 ± 49.3          | 144.08 ± 63.0          | 29 ± 4               | 36 ± 4          | weak NeII:N11.7 |
| 20 | J2000.0           | 153.01 ± 47.7          | 144.29 ± 61.4          | 493 ± 52             | 123 ± 13        | southern limb of “bubble” (E1 of AL95) |
| 21 | J2000.0           | 153.44 ± 49.6          | 144.73 ± 63.3          | —                    | 31 ± 3          | weak NeII:N11.7 |
| 22 | J2000.0           | 154.28 ± 54.2          | 145.57 ± 67.9          | 142 ± 16             | —               | —                 |

[1] Source designation is relative to (09°55′, +69°40′) in J2000.0 and (09°51′, +69°54′) in B1950.0. The prefix “I” in the designation refers to the fact that these are infrared coordinates. The final column states cross-identification with the radio catalog of M02 (McDonald et al. 2002), or with diffuse structures in AL95 (Achtermann & Lacy 1995). In some cases, other comments are given.

[2] These sources were used for astrometric calibration.
and infrared, and given that some natural variation amongst the strengths of the \([\text{Ne II}]\lambda 12.81 \mu\text{m}\) line dominating the NeII filter is expected.

Such a registration procedure is not foolproof, so we have carried out cross-checks of our astrometry against published (comparatively) low spatial resolution data mentioned previously: the \([\text{Ne II}]\) line map of AL95 and 12.4 \(\mu\text{m}\) imaging from TG92. A near-perfect astrometric match is found with the former at the center of our field of view, but with an increasing radial offset toward the edges. The 12.4 \(\mu\text{m}\) images of the latter show a small systematic offset to larger right ascension with respect to both our astrometry and the line map of AL95. All of the above relative offsets lie below \(\sim 1.4^\circ\) and are unlikely to be significant, because the absolute position accuracies or spatial resolution available to these authors were \(\sim 1.5^\circ\).

The above comparisons are self-consistent with our astrometric solution, and we estimate the absolute positional accuracy of our images to be better than 1\". Further detailed checks must await high resolution data and more cross-identifications over a larger field of view.

7. Results

7.1. Comparison with Near-IR Images

We start with a qualitative comparison of the overall distribution of stars with that of dust. For the stellar distribution, we used a 1.6 \(\mu\text{m}\) NICMOS image obtained from the Hubble Space Telescope archive, and its astrometry was calibrated by using the association found by Kong et al. (2007, see their figure 8) for their point source designated as J095510.0 in Chandra X-ray imaging. Figure 5 presents our NeII image and the NICMOS 1.6 \(\mu\text{m}\) image. These have been overlaid on to a single image in figure 6. There is a distinct anti-correlation between the visibility of stars at near-IR wavelengths and the appearance of mid-IR dust. In particular, the group of well-known super-star clusters MGG-7, 9, and 11 (cf. figure 8 of Kong et al. 2007) neatly nests within the mid-IR gaps. Other clusters, e.g., MGG-3, 6, 8, q, and other massive
agglomeration of stars (McCray et al. 2003), all appear where the mid-IR emission is the weakest. Heavy and patchy dust extinction is known to affect the core of the galaxy — \( A_V > 25 \) mag (Willner et al. 1977; Rieke et al. 1980; O’Connell et al. 1995) — which may easily be higher within individual clumps. Using the standard interstellar extinction law (Rieke & Lebofsky 1985), the corresponding \( H \) band extinction is expected to be \( A_H \approx 4 \) mag. Thus the effect of dust is sufficient to cause the anticorrelation between mid-IR and near-IR structures.

7.2. Comparison with X-Ray Images

We also carried out a comparison between two long X-ray images obtained from the Chandra archive: sequences 600735 and 600736 with observation dates of 2009 June 24 and 2009 July 1, respectively. In each case the center of M 82 lies on the S3 chip of Advanced CCD Imaging Spectrometer (ACIS). Results presented here use CIAO v4.2 and the CALDB v4.3.0 calibration database. The data were recalibrated using VFAINT cleaning, with random pixelization removed and bad pixels masked, following the software “threads” from the Chandra X-ray Center (CXC)\(^4\) to make new level 2 events files. Only events with the recommended grades of 0, 2, 3, 4, and 6 were used. The observations were free from large background flares, and after removal of time intervals when the background deviated more than 3\(\sigma\) from the average, the exposure times for sequences 600735 and 600736 were 118.413 and 118.054 ks, respectively. The default astrometry attached to the images was found to agree with the data, presented by Kong et al. (2007), to within \( \pm 0.3 \) and no further refinement was done. In figures 5 and 6, an exposure-corrected 1.2–5 keV merged image of the two observations is included. Note that the brightest source in the field ULX X-1 is likely to be piled up (see also Feng & Kaaret 2010) and a “halo”-like count depression visible in figure 5 seems to be caused by this. There is also a faint readout streak extending from the source position in both directions on the ACIS data. But these effects are not relevant to our work, because the chip regions used for spectral analysis (later in section 8) do not overlap with this; nor do we use this source for astrometric calibration or any other analysis.

There are hints of association of the mid-IR wind streamers with structures in the diffuse X-ray emission at faint levels. There is also a conspicuous dust lane of extinction which bisects the stellar distribution (e.g., O’Connell et al. 1995), and this appears to be associated with cold gas obscuration as well. This is manifest as a sharp decrement in the diffuse galactic X-ray emission (easily visible in the bottom panel of figure 5) coincident with the near-IR deficit. The mid-IR emission avoids several spots along this band (in particular, near the dynamical center) which may be sites of extremely thick and cold absorbing material. Detailed analysis of these individual structures is left for future work.

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\(^4\) (http://cxc.harvard.edu/ciao).
With regard to the X-ray point sources, the most important coincidence is that of source #18, which will be discussed in detail in section 8. The well-known bright ultraluminous X-ray sources (ULXs) known in the core of M 82 do not show bright mid-IR counterparts. There is, however, one potential match. Kong et al. (2007) note that their X-ray source J095551.0 (which we use for the NICMOS astrometric calibration in the previous section) coincides with the radio source 42.21 + 59.2 [B1950.0] from M02. Our source #11, I51.01 + 45.7 [J2000.0], lies at a separation of 0.5'' from the radio position. This offset, combined with the fact that the mid-IR counterpart is elongated (roughly along the north–south direction; figure 3), makes cross-identification uncertain. But there are two noteworthy points: (1) M02 also found an extension for the radio counterpart along a similar direction (see also Fenech et al. 2008); (2) our mid-IR counterpart bridges the near-IR + X-ray position and the radio one. So we tentatively assign this source as the fifth H II region identified in the mid-IR (it is marked in figure 4). As discussed by Kong et al. (2007), the X-ray counterpart may be a ULX hosted within the star cluster detected by M02 in the radio (and also now by us in the mid-IR).

7.3. Discrete Sources

The general source population in the core of the galaxy consists of discrete sources whose emission is superposed over a diffuse radiation field. Of all detected sources, only one (source #8, I50.44 + 48.2, in table 1) appears to be truly point-like based on the structural parameters returned by SExtractor and a FWHM of close to that expected for the diffraction limit. Note that the morphology of source #18, I52.70 + 45.9, which we will discuss further in section 8, is uncertain due to its faintness and the fact that it is affected by low level read pattern noise.

Most of the discrete sources appear extended at our high angular resolution of ≈ 0.4'' (corresponding to a linear scale of ≈ 6–6.5 pc). This is in contrast to the optical and near-IR appearance of super star clusters detected in HST NICMOS imaging, where most were found to have half light physical extents of ~ 3.5 pc or less (O’Connell et al. 1995; McCrady et al. 2003). Our detected dust features may then be a result of large scale outflows from the starburst regions.

The measured source centroids and fluxes are listed in table 1, and the sources are identified in figure 3. There is good overall agreement in the emission structures between the two images, though the NeII filter shows a greater number of significant individual detections as compared to N11.7, especially toward the outer parts of the field of view. Many sources have NeII filter fluxes higher than the corresponding N11.7 filter fluxes by factors of several at least, meaning that the [Ne II]/N12.81 \( \mu \)m dominates in these cases. This is true for all the H II regions cross-matched with the radio catalog of M02, which is consistent with the fact that this emission line is a strong star-formation indicator, and also why more sources are detected in the NeII filter.

In table 1, we comment on some source properties and associations with ionized gas sources identified by AL95. In particular, we have found additional structure to their “E1, W1, and W2” peak emission sites on the eastern and western limbs, and on the western ridge of [NeII] line emission. A couple of sources are also found on the faint “bridge” of emission connecting the eastern and western limbs of the ring. Finally, two of the tabulated sources (#19 and #21) have NeII fluxes of less than 1.5 times the continuum flux in the N11.7 filter, much less than in other cases. This may suggest atypical SEDs with continua rising to shorter wavelengths. Upon examining figure 3, though, it seems that extended emission is present in the NeII filter at the positions of both these sources, but SExtractor is simply unable to isolate it from the highly clumpy diffuse background. In fact, simulating the addition of a weak point source at the position of #21 in the NeII filter suggests a limit of ~ 90 mJy which, in turn, implies a NeII/N11.7 flux ratio consistent with the distribution of flux ratios for detected sources in table 1.
**7.4. Diffuse Features and Galactic Emission**

Underlying the discrete sources is a diffuse emission field from the galaxy which completely dominates the radiated flux. Integrating all observed photon counts over the COMICS field of view yields total fluxes of 55 Jy in the N11.7 filter and 108 Jy in the NeII. Systematic uncertainties from detector cosmetics and the standard star absolute calibration dominate here (section 5), for which we allow for 10% variations across the full field. The 11.7 μm flux is within a factor of 2 of the continuum flux reported by Beirão et al. (2008) for their “total” aperture. This comparison is likely to be full consistent, given the difference in aperture size and position used, perhaps some contribution of the 11.2 μm polycyclic aromatic hydrocarbon feature to our broad-band photometry, and absolute cross-calibration uncertainties. Removing the combined flux of the discrete sources identified in table 1 gives 53 and 106 Jy for the two filters. This diffuse emission possesses substantial substructure, of which we highlight a few specific aspects.

The most striking features of our high resolution imaging are several wind “streamers”, which stand out better in figure 7 which has been smoothed by convolution with a square top hat kernel $5 \times 5$ pixels ($0.67 \times 0.67$) wide, in order to enhance faint diffuse features. Most of these are visible on the northern side, with an orientation roughly perpendicular to the major axis of the galaxy. The longest of these in our image is a chimneylike straight structure, with a linear extent of over 7”, or $\sim 120 \text{pc}$. Chopping in the mid-IR cuts out a lot of extended emission. So, we are undoubtedly seeing only the inner regions of much larger streamers and chimneys which have been detected on wider scales (e.g., Engelbracht et al. 2006; Kaneda et al. 2010).

Toward the northeast of the field of view, two structures extend outward and curve in toward one another, resembling the edges of a limb-brightened bubble. Assuming...
a circular shape, the projected diameter of this feature is \(~8''\),
corresponding to a physical size of \(~140\) pc. Limb-brightening is much less pronounced near the top, which may suggest

wind rupture, if real. Ruptured bubbles are a natural consequence of over-pressurization of outflowing hot gas in the superwind model which explains the burst of star formation in the core of M 82 (e.g., Chevalier & Clegg 1985; Heckman et al. 1990). If there is entrained clumpy dust within this outflow, the dust distribution will follow that of the gas. On the other hand, there is no obvious evidence from multiwavelength data that this bubble is filled in with hot plasma. Its reality as a bubble or as two separate streamers needs confirmation from further observations.

These various features do not point back to a single site of energy ejection. The starburst in M 82 is known to occur in a “ring”, rather than a compact nuclear concentration (e.g., Nakai et al. 1987; AL95), and the mid-IR emitting hot dust indeed traces out portions of this ring. Multiple burst events of dust expulsion along the entire inner \(~500\) pc region of this ring are required to explain the data.

7.5. Dust Temperature and Mass

The mass of the hot, mid-IR emitting matter may be estimated by assuming optically thin thermal radiation from uniform spherical dust grains. The largest uncertainty in this estimate is the unknown and spatially variant dust temperature. Telesco and Harper (1980, hereafter TH80) were able to fit a modified black body emission model with a temperature of \(~45\) K for the dust emitting at far-IR wavelengths of

Fig. 8. Archival wide beam fluxes of the integrated emission from the central regions of M 82 from Telesco and Harper (1980) (beyond 40 \(\mu\)m) and Rieke and Low (1972) (5, 10.5, and 21 \(\mu\)m) overplotted with our integrated COMICS 11.7 \(\mu\)m flux (red box). The left green and right blue curves represent modified black bodies with temperatures of 45 K (cf. figure 1 of TH80) and 160 K, respectively. The black curve is the sum of these two.

Fig. 9. Magnified images (\(9''\) wide \(\times\) 6'' high) on the position of the AGN candidate (source #18) in the mid-IR (top left: COMICS NeII filter) and near-IR (top right: HST NICMOS F160W filter). The X-ray images at the bottom are for energy ranges of 0.5–2 keV (left) and 3–7 keV (right). Because the PSF of ACIS is larger than in the IR, both X-ray images are zoomed out by a factor of two; the dashed box in the bottom-right panel shows the field size of the IR panels. The scale bar notches denote 1'' offsets from the source position in both RA and Dec. The regions used for spectral extraction of the target and background are shown in the 0.5–2 keV image as the gray (magenta) circular and polygonal apertures, respectively. A secondary annular background region used for a consistency check is also shown in white (yellow).
41–141 μm over the central ~900 pc region. They also found the observed fluxes at shorter wavelengths from 2–21 μm to overestimate the thermal model predictions by many orders of magnitude, meaning that hotter dust components characterize the mid- and near-IR emission.

In figure 8, we overplot the 5–41 μm fluxes and 45 K thermal model from TH80, along with our integrated N11.7 filter flux. There is some nonnegligible uncertainty resulting from varying beam sizes and centroids amongst the data plotted in this figure, so we do not carry out a detailed fit. But a qualitative comparison is reasonable if the flux is mostly centrally concentrated. If a two-temperature-only model is assumed, we find that a modified black body with flux density varying as \( v^{1.5} B_{v,T} \) (where \( B_{v,T} \) is the Planck function at frequency \( v \) and temperature \( T \)) is a fair representation of the 10.5–21 μm integrated source fluxes for \( T \sim 160 \) K. The emissivity power-law index of 1.5 has been assumed to be identical to that found for the cooler dust by TH80. This model is also plotted in figure 8 (normalized to our 11.7 μm data), and shows that the 5 μm excess requires other even hotter dust components, if this emission is thermal in origin.

Using this model, the dust mass may be estimated by employing the infrared emissivity relation of Hildebrand (1983),

\[
M_d = \frac{4\pi a \rho D^2}{3} \frac{F_v}{Q_{v,a} \pi B_{v,T}}
\]

where \( M_d \), \( D \), \( a \), and \( \rho \) are the dust mass, galaxy distance, grain radius, and specific density, respectively. \( F_v \) and \( Q_{v,a} \) are the observed flux density and the grain emissivity. Assuming emission from the grain surface into all hemispherical solid angles gives the factor of \( \pi \) in the denominator. Taking canonical values of the size and density for a graphite grain composition gives

\[
M_d = 1.44 \times 10^{-27} \left( \frac{a}{0.1 \mu m} \right) \left( \frac{\rho}{2.26 \, g \, cm^{-3}} \right)
\]

\[
\times \left( \frac{D}{pc} \right)^2 \left( \frac{F_v}{Jy} \right) Q_{v,a}^{-1} B_{v,T}^{-1} M_\odot
\]

for \( B_{v,T} \) expressed in W m\(^{-2}\) Hz\(^{-1}\) sr\(^{-1}\). A mean 11.7 μm emissivity of \( Q_{v,a} \approx 0.009 \) for graphite grains with diameter of \( a = 0.1 \mu m \) is used (Draine 1985). The observed total flux and model temperature then imply \( M_d \sim 950 M_\odot \) for the hot dust. In comparison with the mass of cooler 45 K dust determined by TH80, this is ~500 times lower.

8. Candidate AGN

Our target #18, I52.70+45.9 [J2000.0], has a uniquely interesting story. In our astrometry-corrected images, it is found to be coincident (within ~0’:1) with the radio source 44.01+59.6 [B1950.0] from McDonald et al. (2001, and references therein). Based upon several lines of evidence, it has been suggested that this may be a weak active galactic nucleus (AGN) in M82. The evidence includes the atypical radio SED, detection of OH maser satellite lines and also a possible elongated radio jet (Wills et al. 1997, 1999; Seaquist et al. 1997). Other detailed studies have shown that its SED is not atypical for an SNR, and it has an expanding shell with an expansion velocity of 2700 ± 400 km s\(^{-1}\) (Allen & Kronberg 1998; Fenech et al. 2008). Several hard X-ray AGN searches have been carried out over the years (Tsuru et al. 1997; Ptak & Griffiths 1999), and a potential counterpart has been detected with ROSAT (Stevens et al. 1999, cf. their source X-3) and even Einstein (Watson et al. 1984, who also suggested this as a possible nucleus, based on its proximity to the 2.2 μm core). But there is considerable diffuse soft X-ray emission in this region, and the high resolution of Chandra is required for resolving the complex unambiguously (e.g., Matsumoto et al. 2001). No unambiguous and strong X-ray: radio association to our knowledge has been reported to date. The source lies close to, but not exactly at the dynamical center of the galaxy. It lies 4’1 (70 pc) and 2’1 (36 pc) from the radio and optical kinematic centers quoted by Weliachew, Fomalont, and Greisen (1984, see also O’Connell & Mangano 1978; errors are ~1.5”–2” in each coordinate). In summary, the nature of this object still remains uncertain.

In figure 9, we present zoom-in images of the source position in the mid-IR (our NeII filter), the near-IR (NICMOS 1.6 μm), and X-rays (Chandra ACIS 0.5–2 keV and 3–7 keV). There is no pointlike source in the near-IR, but it is detected significantly in our NeII image. A source also clearly appears in X-rays, especially at hard energies. We designate this source as CXOU J095552.7+694046 (with J2000.0 coordinates of 09:55:52.7+69:40:45.8, or J095552.7 for short). Its position relative to other X-ray sources within the core of M82 discussed by Kong et al. (2007) is shown in the bottom panel of figure 5. We now present analysis of the new long-exposure Chandra archival data analyzed herein. In the next section, we will examine the broad-band SED and comment on the source nature.

8.1. Chandra X-Ray Data

First, we extracted a radially averaged surface brightness profile of the source, and compared this to a simulated PSF image. The PSF was constructed using the Chandra ray tracing package CHART\(^\text{5}\) assuming observational parameters including nominal and source coordinates, roll angle, and ACIS-S chip identical to those for the analyzed data (the sequence 600735 was used for this comparison). The ray trace was then projected onto the detector plane and a PSF events file generated using MARX. The profile of the source for photons extracted over the hard 3–7 keV energy range, compared to the PSF expected for 4.5 keV photons, is shown in figure 10. A constant background level corresponding to the outermost radial bin has been removed. The source appears to be consistent with a point source, at least within the core. There may be evidence of an extended “wing” around 1’ radius, but systematic effects of the (position-dependent) underlying galactic background cannot be ruled out.

Next, the X-ray spectrum of the source was extracted. A circular aperture of radius 1’25 was used to accumulate source counts. The diffuse galactic flux around the source is clumpy and affected by cold gas absorption to its immediate north. An irregularly shaped polygonal region surrounding

\(^5\) [http://cxc.harvard.edu/chart].
the source was selected for background subtraction, avoiding nearby point sources as well as strong absorption to the northwest. These regions are shown in figure 9. For spectral extraction the CIAO task `psextract` was followed by `mkacismf` and `mkarf` to apply the latest calibrations. Models were fitted jointly to the two separate observations. Fitting was performed in XSPEC (Arnaud 1996) and includes absorption along the line of sight in our Galaxy fixed at a column density of $N_{\text{H}} = 4 \times 10^{20} \text{cm}^{-2}$ (based on the data by Dickey & Lockman 1990).6

A minimum grouping of 30 counts per spectral bin was applied for fitting and uncertainty determination with the $\chi^2$ statistic. A fit to the resultant 0.7–6.8 keV spectrum (ignoring “bad” bins and energies below 0.5 keV) with a single power law component results in a hard power law with photon index $\Gamma = 1.11 \pm 0.08$ (all uncertainties are quoted at 90% confidence), but with an unacceptable goodness of fit $\chi^2 = 175$ for 100 degrees of freedom (dof), with residuals suggesting the presence of emission features below 4 keV including those from highly ionized Si, Ne, and Ar. Several models, including a combination of absorbed power laws, or a power law combined with a thermal (APEC) plasma model (Smith et al. 2001) were tried. Although some of these yield statistically acceptable fits, the power law slope above 3 keV turns out to be very soft, with $\Gamma$ restricted to $\geq 2$–3 in all cases. Furthermore, residuals suggesting additional emission bands still remain unaccounted for.

The best model is a combination of two absorbed thermal

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6 Using the `colden` program provided by CXC.

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Fig. 10. Top: Azimuthally averaged Chandra ACIS-S radial surface brightness profile of J095552.7 (points with error bars). The empty gray squares show the normalized count profile before background subtraction. The filled black circles denote the normalized net profile, and these can be compared to the expected PSF from a point source histogram. The source profile is extracted from the 3–7 keV image, and the PSF from ray-tracing of 4.5 keV photons. Bottom left: X-ray spectrum and residuals to a fit with two absorbed thermal plasma models. Data from both analyzed observations (black and gray/red for sequences 600735 and 600736, respectively) are included. The two thermal models are shown as the dotted lines. Bottom right: Ungrouped spectrum around the Fe K line and best-fit model from the left panel (rebinned to obtain a minimum 2$\sigma$ significance for plotting only).
plasmas, with temperatures of 0.6 keV and 2.6 keV, absorbed by significantly different columns of $N_{\text{H}} = 8 \times 10^{21}$ and $4.3 \times 10^{22}$ cm$^{-2}$, respectively. With abundances fixed at Solar, assuming the Lodders (2003) abundance table for both temperature components, a $\chi^2$/dof = 101.5/96 is found. The spectrum with this best fit is shown in figure 10 and the parameters are listed in table 2. Adopting only a single absorber produces an unacceptable fit. Regarding abundances, assuming a yield appropriate for SN II instead (Nomoto et al. 2006, averaged over a Salpeter initial mass function from 10 to 50 $M_\odot$, with a progenitor metallicity of $z = 0.02$) produces a fit similar to the best one. Letting the abundances of the two components vary also does not improve $\chi^2$ significantly. On the other hand, those for SN Ia (Iwamoto et al. 1999, their W7 model) yield a progenitor metallicity of $z = 0.02$, consistent with highly ionized Fe at 6.7 keV, and not the neutral Fe at 6.7 keV; in other words, the line is significantly detected (despite large uncertainties on its strength) and its center energy is consistent with highly ionized Fe at 6.7 keV, and not the neutral line energy of 6.4 keV.

### 8.2. Fe K Emission Line

The high temperature plasma should also emit a strong ionized Fe line around 6.7 keV, near the limit of the binned energy range available. In order to analyze this line, in figure 10 we show the ungrouped spectrum around 6.7 keV, overplotted with the best fit model determined above (binning is applied for display purposes only). The default model clearly produces a line feature also seen in the data.

We estimate its significance in a couple of ways. Accumulating net source counts over 6.5–6.9 keV after subtracting off the model continuum measured at the ends of this energy range, and comparing these counts with the total (background inclusive) counts in the same range, yields a simple Poisson signal/noise ratio of 2.4 and 3.1 for the line feature in the two Chandra data sets, respectively. Another estimate can be obtained by parametrizing the continuum as a power-law locally, and then fitting the line as a Gaussian superposed on this. The energy range of 5–8 keV is used in order to estimate the continuum, and we assume a Gaussian width $\sigma$ fixed at 10 eV. The $C$-statistic is the appropriate one to use for ungrouped data (Arnaud 1996). We find a line energy of 6.68 (±0.03) keV and a 90% equivalent width range of 0.6–4 keV; in other words, the line is significantly detected (despite large uncertainties on its strength) and its center energy is consistent with highly ionized Fe at 6.7 keV, and not the neutral line energy of 6.4 keV.

### 8.3. Comparison with Prior Archival Data

Detection of any flux variability can be important for understanding the nature of the source. The fluxes inferred from the two Chandra observations above are consistent with each other, and one must examine longer timescales. Searching in the Chandra archive for other data, one of the earliest ACIS-S observations covering the position of this source is sequence 600270 with observation date 2002 June 18. The exposure time after flare removal is only 18.03 ks, but there is a long time baseline of $\sim$ 7 yr to the 2009 observations analyzed in previous sections.

We reduced and analyzed this archival data set in a similar manner to the 2009 observations. The extracted net spectrum is shown in figure 11. Fitting with the same absorbed double thermal model as in subsection 8.1 yields parameters consistent with those listed in table 2 (though with much larger uncertainties), and a flux $F_{0.5-10\text{keV}} = 1.06^{+0.14}_{-0.10} \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$, corrected for Galactic absorption only. The 90% confidence interval overlaps with the flux determined from the 2009 observations (subsection 8.1).

Thus, there is no indication for strong flux variability on a timescale of several years either. A similar inference has also been reached by Chiang and Kong (2011) in a recent

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**Table 2. Spectral fit for the X-ray counterpart to source #18.**

| Model components | Value                                      |
|------------------|--------------------------------------------|
| PHABS            | $4 \times 10^{20}$ cm$^{-2}$               |
| WABS1            | $7.9^{+1.0}_{-1.1} \times 10^{31}$ cm$^{-2}$ |
| $kT_1$           | $0.58^{+0.07}_{-0.03}$ keV                 |
| APEC1 Abundance norm1 | $7.42^{+2.65}_{-0.26} \times 10^{-5}$       |
| WABS2            | $4.28^{+1.16}_{-1.05} \times 10^{22}$ cm$^{-2}$ |
| $kT_2$           | $2.56^{+0.82}_{-0.46}$ keV                 |
| APEC2 Abundance norm2 | $1.99^{+0.77}_{-0.66} \times 10^{-41}$      |

* X-ray joint spectral fit to the two Chandra archival data sets analyzed. The model is PHABS (WABS1*APEC1 + WABS2*APEC2), with abundance fixed to that of Lodders (2003). Errors correspond to 90% parameter uncertainties on a single interesting parameter, when not fixed. This model returns a statistic of $\chi^2$/dof = 101.5/96.

† The units of norm are $10^{14}$ cm$^{-3}$.
analysis of other observations (their source designation is CXOU J095552.8+694045). Our comparisons limit any flux variations to less than 20%.

9. Discussion

We have presented the highest resolution imaging of the nuclear regions of M 82 to date in the mid-IR. The Subaru diffraction limits at wavelengths of 11.7 and 12.81 μm are 0.36 and 0.39, respectively. Compared to the previous best resolution observations (the 12.4 μm imaging with PSF of 1″ presented by TG92), our images have PSFs improved by factors of 3.1 and 2.8 at 11.7 and 12.81 μm, respectively, and we cover a core region larger by a factor of at least two. The referee also made us aware of a conference proceeding by Ashby et al. (1994), where an image at 11.7 μm with an angular resolution of 0.6″ is presented. The absolute astrometry of their image agrees to within 1″ with our work, as well as with the work of AL95 and TG92. To our knowledge, no further details have been published.

Multimwavelength image comparisons show an anticorrelation between the observed stellar distribution (probed in the near-IR) and the distribution of warm dust that we probe. This means that obscuration in these dusty regions is heavy enough to deplete even near-IR radiation.

Our observations provide the best view of the base of the dusty superwind that is known to exist in this galaxy, and reveal several elongated features on projected physical scales of up to \( \ell = 120 \) pc at least. If the mid-IR emitting dust is mixed in with and entrained in outflowing gas, then the travel time \( (t) \) is

\[
 t = 5.9 \left( \frac{\ell}{120 \text{ pc}} \right) \left( \frac{200 \text{ km s}^{-1}}{v} \right) \times 10^5 \text{ yr},
\]

where a velocity of \( v = 200 \) km s\(^{-1} \) identical with that found by Nakai et al. (1987) for the molecular gas is used as reference. This time period suggests recent energy input from young starbursts. The kinetic energy required to expel this dust is only a fraction of that channeled into the total gas mass, and so expulsion by SNe occurring at various locations around the ring of star-formation can easily account for this (Nakai et al. 1987).

Using the integrated fluxes over the COMICS field-of-view, we are able to describe the broad-band mid-IR diffuse emission with a \( T = 160 \) K modified black body with a hot dust mass of \( ~ 1000 \) M\(_\odot\), in addition to the 45 K cool dust component responsible for the far-IR emission. Assuming a standard gas/dust ratio of 100, the mass of the gas associated with the mid-IR emitting dust is then \( ~ 10^2 \) M\(_\odot\). This is lower than the ionized gas mass of \( 2 \times 10^6 \) M\(_\odot\) (Willner et al. 1977; TH80) by a factor of \( ~ 20 \), meaning that the ionized gas may be the predominant environment for the hot dust that we are observing. The cooler dust, on the other hand, is likely to be tracing the distribution of molecular gas (TH80).

More than 20 discrete sources are detected, and most are found to have extended profiles. Matching with radio catalogs suggests that we resolved at least four (and tentatively, five) H II regions in the mid-IR for the first time. These H II regions have monochromatic continuum dust luminosities ranging from \( vL_{17.9\mu m} = 2 \times 10^8 L_\odot \) (radio ID 39.29+54.2) to \( 8 \times 10^6 L_\odot \) (41.17+56.2), consistent with being powered by embedded super star clusters similar to those seen in some other nearby galaxies (e.g., Galliano et al. 2008).

As seen in figure 6, no source is detected at the position of the radio transient identified by Brunthaler et al. (2009) as SN2008iz, the brightest radio SNR in M 82 over the past 20 yr. The start of bright radio flaring activity is limited to the period from 2007 October 29 to 2008 March 24. Our observations were carried out one month after the final set of follow-up radio observations on 2009 April 4 reported by Brunthaler et al. (2009), when they found the source to have an integrated 22.2 GHz flux of 9.2 \( \pm 0.2 \) mJy. Our flux limits are \( F_{\ell NeII} < 38 \) mJy and \( F_{\ell N11.7} < 18 \) mJy, assuming a point source of angular size equal to the diffraction limits in each filter. In general, there is little overlap between confirmed SNRs and mid-IR detections. Additionally, no mid-IR counterpart is detected at the location of the unusual radio transient found by Muxlow et al. (2010). The source appeared on radio images obtained within the period of 2009 May 1–5 — contemporaneous with our mid-IR observations — and was not present one week before. It is located \( ~ 1″ \) from the position of our source #18 (see also Kong & Chiang 2009 for an identification of the X-ray counterpart). We estimate point source upper limits of 34 mJy and 15 mJy in the NeII and N11.7 filters.

No space observatory is foreseen to have a better resolving power than Subaru at \( ~ 10 \) μm, though the Mid InfraRed Instrument (MIRI) on board James Webb Space Telescope (JWST) should provide excellent sensitivity for only a modest loss in angular resolution at the same wavelengths (e.g., Wright et al. 2004). MIRI is also expected to have a field of view larger by a factor of \( \geq 2 \) on a side, making source identification much more secure. On a longer timescale, the European/JAXA mission Spica (Nakagawa 2004) will be crucial for deep far-IR studies. On the ground, the Gran Telescopio Canarias, with a primary mirror diameter of 10.4 m, can improve the resolution slightly to \( 0.3 \) under good observing conditions.
Even better resolution must await larger ground-based observatories such as the Extremely Large Telescope. This will not be diffraction-limited under natural seeing conditions and will require additional adaptive optics capabilities in the mid-IR to improve upon the results presented herein.

9.1. Nature of AGN Candidate Source

The puzzling radio source 44.01+59.6 has a significant mid-IR Ne II detection (our source #18, 152.70+45.9), and is also coincident with a source (J095552.7) visible in high-resolution X-ray images, to well within our estimated absolute positional uncertainties. From Chandra data, it is immediately apparent that the X-ray spectrum is not consistent with that of AGN, which usually displays broad-band power-laws with photon-indices \( \sim 1.9 \) characteristic of radiatively efficient accretion (e.g., Mateos et al. 2005). Low luminosity AGN with radiatively inefficient flows or jets, too, usually displays hard X-ray continua (e.g., Yu et al. 2011). Similarly, one can argue against direct association with other kinds of accreting sources such as X-ray binaries.

The detection of a strong He-like Fe line instead of a neutral line centered on 6.4 keV implies the absence of cold reflecting matter, also atypical for an accreting source. Highly ionized lines have actually been attributed to heavily obscured AGN in some cases (e.g., Iwasawa et al. 2005; Nandra & Iwasawa 2007, and references therein), though on larger scales. In such a scenario, the AGN itself is not readily apparent; rather, the visible spectrum is dominated by surrounding gas which is irradiated by the AGN along directions out of our line of sight. If this is true for the case of source J095552.7, the underlying accreting object (be it an AGN or an X-ray binary) could power the radio jet found by Wills et al. (1999) and also provide a ready source where accreting gas is in rotation (as inferred from the maser lines found by Seaquist et al. 1997). But this would also result in X-ray photoionization spectral features or even an ionized reflection continuum. An extra layer of optically thick obscuration is then also required (in addition to the two that we detect) with an extreme covering factor very close to unity so as to completely hide the reflection continuum and any neutral Fe K line. This is not consistent with the detection of a jet which would be expected to decrease the covering factor by clearing away some surrounding matter.

Finally, the 2–10 keV luminosity of \( 5 \times 10^{38} \text{erg s}^{-1} \) means that the source is unlikely to have a bolometric X-ray power which would place it in the ULX regime (e.g., Makishima et al. 2000) because of the steep spectra of the fitted thermal models. Thus, our analysis allows us to reach some firm conclusions as to what the source is not. The true source nature still remains uncertain, though, and in the following, we discuss plausible alternatives.

In addition to our [Ne II] image, the source appears most prominently as a compact object in hard X-rays. One possibility may then be that both the mid-IR and the hard X-ray components are associated with the SNR visible in the radio. To test this, we may compare the source power to that of Cas A, a powerful and young Galactic SNR. From Suzaku observations summed over the entire remnant, the 4–10 keV X-ray luminosity of Cas A is determined to be \( L_{4-10 \text{ keV}} \sim 4 \times 10^{35} \text{erg s}^{-1} \) (Maeda et al. 2009). This is \( \sim 150 \) times smaller than the deabsorbed X-ray luminosity \( L_{4-10 \text{ keV}} \sim 6 \times 10^{37} \text{erg s}^{-1} \) that we find for our source, using the high temperature APEC component alone (subsection 8.1). This requires that the electron density \( n_e \) in the X-ray emitting interstellar medium (ISM) around source #18 be much larger than in the case of Cas A. \( n_e \) may be determined by using the normalization values returned by the APEC2 component and the emission volume which, in the scenario under consideration here, should correspond to the volume of the radio-emitting plasma. Fenech et al. (2008, see their table 3) measure a diameter of 0.86 pc for the SNR, using which yields an electron density of \( n_e \sim 1.75 \pm 0.3 \times 10^{-3} \text{cm}^{-3} \). A low plasma filling factor would only push this value up. This is, indeed, much larger than typical ISM densities of 1–10 cm\(^{-3}\) relevant for Galactic SNRs. We also note that the present limit on any X-ray variability in the source (\( <20\% \) over 7 yr) derived from archival data comparisons in subsection 8.3 is consistent with the observed smaller flux changes in Cas A over similar timescales (e.g., Patnaude et al. 2010). The detected collimated radio jet may then suggest some kind of axisymmetry in the progenitor (e.g., a powerful binary merger event). It is interesting to note that the \( \sim 45 \) pc length of the jet measured by Wills et al. (1999) may be explained as relativistic expansion for a duration very close to the free expansion age of 140 yr for the radio SNR shell measured by Fenech et al. (2008).

On the other hand, the mid-IR power for source #18 \( (\lambda L_{\lambda(12.81 \mu m)} = 1.5 \times 10^{40} \text{erg s}^{-1} ) \) is in excess of the integrated 12 \( \mu m \) IRAS power of Cas A \( (\lambda L_{\lambda(12 \mu m)} = 5 \times 10^{36} \text{erg s}^{-1} ) \) by a much larger factor of \( \sim 3000 \). But given the unknown dust temperature, the fraction of freshly formed versus ambient heated dust, and the fact that our NeII filter flux is likely to be dominated not by continuum but by the [Ne II] 12.81 \( \mu m \) line (which is known to be a strong cooling line for SNRs, e.g., Rho et al. 2008), further comparison of the mid-IR fluxes is difficult.
The other possibility to consider for the X-ray thermal plasma components is that of a hot ISM phase in a compact star cluster. In fact, collisionally ionized plasmas covering a wide range of temperatures have been previously inferred to exist within starburst galaxies (e.g., Iwasawa et al. 2005; Ranalli et al. 2008; Strickland & Heckman 2009), though on larger scales. Figure 12 shows the compiled radio–to–X-ray fluxes for source #18. A mid-IR flux dominating the SED is consistent with an origin in a starburst, though this is not a unique solution. The detection of two distinct layers of absorption (subsection 8.1) may also suggest a scenario which combines the above possibilities as follows. The hot X-ray thermal plasma and the radio counterpart could both be associated with an SNR, which is embedded within a host star cluster. The high column density affecting the APEC$_2$ component (table 2) may easily be explained by strong local absorption within molecular clouds, for instance. The pointlike profile of the hard X-ray data is also consistent with this. The cluster, on the other hand, could appear prominently in soft X-rays and also in the mid-IR. The comparatively low absorption affecting this component is then due to gas along the plane of the galaxy on larger scales.

Further insight into the nature of this source will be possible if it can be isolated at longer wavelengths characterizing the peak of typical star-formation SEDs (this may be within reach of JWST), or through detection of spectral features in the submillimeter with ALMA. Subsequent long Chandra exposures would be useful for placing tighter constraints on X-ray variability. Meanwhile, the question whether M 82 hosts an AGN or not remains to be answered.

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