Low Radio Frequency Observations and Spectral Modelling of the Remnant of Supernova 1987A

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ABSTRACT

We present Murchison Widefield Array observations of the supernova remnant (SNR) 1987A between 72 and 230 MHz, representing the lowest frequency observations of the source to date. This large lever arm in frequency space constrains the properties of the circumstellar medium created by the progenitor of SNR 1987A when it was in its red supergiant phase. As of late-2013, the radio spectrum of SNR 1987A between 72 MHz and 8.64 GHz does not show any deviation from a non-thermal power-law with a spectral index of $-0.74 \pm 0.02$. This spectral index is consistent with that derived at higher frequencies, beneath 100 GHz, and with a shock in its adiabatic phase. A spectral turnover due to free-free absorption by the circumstellar medium has to occur below 72 MHz, which places upper limits on the optical depth of $\lesssim 0.1$ at a reference frequency of 72 MHz, emission measure of $\lesssim 13,000 \, \text{cm}^{-6} \, \text{pc}$, and an electron density of $\lesssim 110 \, \text{cm}^{-3}$. This upper limit on the electron density is consistent with the detection of prompt radio emission and models of the X-ray emission from the supernova. The electron density upper limit implies that some hydrodynamic simulations derived a red supergiant mass loss rate that is too high, or a wind velocity that is too low. The mass loss rate of $\sim 5 \times 10^{-6} \, \text{M}_\odot \, \text{yr}^{-1}$ and wind velocity of $10 \, \text{km} \, \text{s}^{-1}$ obtained from optical observations are consistent with our upper limits, predicting a current turnover frequency due to free-free absorption between 5 and 60 MHz.

Key words: supernovae: individual (SN 1987A) – ISM: supernova remnants – radio continuum: general

1 INTRODUCTION

Supernova 1987A (SN 1987A), discovered in the Large Magellanic Cloud (LMC) on 1987 February 23, was the brightest supernova seen from Earth since the invention of the telescope (Kunkel et al. 1987; Koshida et al. 1987;...
Svoboda et al. 1987). The close proximity of SN 1987A, and the detailed information we have about its progenitor, has meant SN 1987A has played a pivotal role in shaping our understanding of core-collapse supernovae, supernova remnants (SNR) evolution, and the physical properties of the circumstellar medium deposited by a supernova progenitor.

Radio emission from core-collapse supernovae generally occurs when the forward shock sweeps up the dense, slow-moving wind generated by a red supergiant progenitor (Chevalier 1982). However, the progenitor to SN 1987A was very different than those normally associated with radio supernovae. It is believed that SN 1987A’s progenitor, Sk-69 202, evolved from a red supergiant into a blue supergiant ~20,000 years before the supernova event (Crotts & Heathcote 1991; Podsiadlowski et al. 2007). While the cause of such a transformation is still debated in the literature (e.g. Woosley et al. 1987; Podsiadlowski & Joss 1989; Collins et al. 1999; Smith 2007), this abnormal evolutionary path for a core-collapsed supernova progenitor has produced a complex environment which the shock from the supernova event interacts with.

For example, the prompt radio emission detected at 843 MHz by the Molonglo Observatory Synthesis Telescope (MOST) (Turtle et al. 1987), which faded to an undetectable flux density in under a year (Ball et al. 2001), is understood to be a consequence of the supernova shock interacting with the low density, fast moving blue supergiant wind (Storey & Manchester 1987). Radio emission was then re-detected ~1200 days after the core collapse (Staveley-Smith et al. 1993), indicating that the forward shock of the supernova event was encountering the denser and slower red supergiant wind in the equatorial plane. This interaction produced the radio shell that is now colliding with the clumpy ring observed at optical wavelengths (Crotts & Heathcote 1991; Plait et al. 1995). The hourglass shape of SNR 1987A, formed from the peculiar evolution of the progenitor (Chevalier & Dwarkadas 1995; Sugerman et al. 2005; Potter et al. 2014), also means the forward shock is interacting with hot blue supergiant wind material beyond the termination region at high latitudes (Zanardo et al. 2010). Currently, >9,600 days since the supernova event, it is understood that the forward shock has egressed the equatorial ring and is now interacting with the HII and hourglass region; a region formed from the blue supergiant wind expanding into the red supergiant wind (Lundqvist 1999; Potter et al. 2014).

While SNR 1987A has been extensively studied across the electromagnetic spectrum, there have been no observations conducted at low radio frequencies (< 0.843 GHz). This was due to SNR 1987A being too low in declination to be observed with Northern Hemisphere radio telescopes, and because SN 1987A occurred after all the low radio frequency instruments in the Southern Hemisphere were decommissioned, such as the Culgoora circular array (Slee 1995). Low frequency radio observations of SNRs can constrain the radio spectrum, providing a unique probe for investigating the circumstellar medium via free-free absorption and insights into the shock acceleration process producing the radio emission (e.g. Kassim 1989; Kassim et al. 1995; Lacey et al. 2001; Brogan et al. 2005). Since intrinsic or extrinsic spectral variations are often subtle, low radio frequency observations are an important key in obtaining a large enough lever arm in frequency space to identify any variation. In particular, low radio frequency observations can place constraints on the electron density of the absorbing medium and the mass loss rate of the progenitor (Chevalier 1982; Kassim 1989; Chevalier 1990; DeLaney et al. 2014). Considering the forward shock of SNR 1987A has now passed through the densest part of the equatorial ring (Potter et al. 2014; Fransson et al. 2015), low frequency observations of SNR 1987A can provide mass loss limits of the progenitor when it was in its red supergiant phase. This is because the detected radio emission from SNR 1987A is dominated by emission from the region between the forward shock, that is propagating into the circumstellar material, and the reverse shock (Chevalier 1982). The temperature and density of the material internal to the reverse shock is such that the radio emission from the interior to the reverse shock is completely absorbed (Chevalier 1982; Lundqvist 1999; Chevalier & Fransson 2003).

In this paper we present the lowest radio frequency observations of SNR 1987A using the Murchison Widefield Array (MWA; Tingay et al. 2013). The MWA is a low radio frequency aperture array which observed SNR 1987A between 72 and 231 MHz as part of its all-sky survey (Wayth et al. 2015). The observations presented in this paper are over an order of a magnitude lower in frequency than the previous lowest-frequency observations of SNR 1987A, allowing us to investigate the surrounding circumstellar medium in a part of frequency space previously unobservable. Combined with gigahertz observations from the Australia Telescope Compact Array (ATCA), these observations provide key insights into the interaction of the supernova shock with the circumstellar medium and its properties. The MWA and the ATCA observations, and the relevant data reduction procedures performed, are outlined in detail in § 2. The resulting radio spectrum and the absorption model fits are described in § 3. In § 4, the implications of these model fits on the mass-loss rate and wind velocity of the progenitor of SNR 1987A are discussed.

2 OBSERVATIONS AND DATA REDUCTION

SNR 1987A was observed by the MWA and the ATCA in late 2013 and early 2014. While not simultaneous, the two ATCA observations bracket the MWA observation with an almost equal gap of three months either side. These observations are summarised in Table 1 and the details about the data reduction processes are described below.

2.1 MWA Observations and Data Reduction

SNR 1987A was observed by the MWA between 72 and 231 MHz on 2013 November 8 as part of the GaLactic and Extragalactic All-sky Murchison Widefield Array (GLEAM; Wayth et al. 2015) survey. The GLEAM survey was conducted by observing the sky between declinations of ~90° and +25° in a two-minute “snapshot” mode, utilising the meridian drift scan technique at seven independent declination settings. SNR 1987A was observed during the drift scan that was centred on a declination of ~55°.

The data reduction process that was performed is described in detail by Wayth et al. (2015) and Hurley-Walker...
Spectral Modelling of SNR 1987A

Table 1. A summary of the observations of SNR 1987A used in the spectral modelling. Note that $v$ represents the central frequency of the observing band, $S_v$ is the total flux density at frequency $v$, and $\Delta S$ is the uncertainty on the flux density measurement. For the MWA measurements $\Delta S$ is the sum in quadrature of the local RMS noise and the systematic uncertainties associated with correcting the deficiencies in the primary beam model. $\Delta S$ for the ATCA measurements is the sum in quadrature of the local RMS noise and the uncertainties in the gain calibration. $a_{pp}$ and $b_{pp}$ are the semi-major and semi-minor axis of the synthesised beam, respectively.

| $v$ (GHz) | $S_v$ (Jy) | $\Delta S$ (Jy) | Epoch       | Telescope   | $a_{pp}$ (´) | $b_{pp}$ (´) |
|-----------|-----------|----------------|-------------|-------------|--------------|--------------|
| 0.076     | 5.1       | 0.8            | 2013 Nov 08 | MWA         | 5.9          | 5.2          |
| 0.084     | 4.9       | 0.7            | 2013 Nov 08 | MWA         | 5.4          | 4.8          |
| 0.092     | 4.7       | 0.5            | 2013 Nov 08 | MWA         | 5.0          | 4.4          |
| 0.099     | 4.6       | 0.4            | 2013 Nov 08 | MWA         | 4.8          | 4.1          |
| 0.107     | 4.5       | 0.3            | 2013 Nov 08 | MWA         | 4.3          | 3.7          |
| 0.115     | 4.2       | 0.2            | 2013 Nov 08 | MWA         | 4.0          | 3.5          |
| 0.123     | 4.0       | 0.2            | 2013 Nov 08 | MWA         | 3.8          | 3.3          |
| 0.130     | 3.9       | 0.2            | 2013 Nov 08 | MWA         | 3.7          | 3.1          |
| 0.143     | 3.6       | 0.2            | 2013 Nov 08 | MWA         | 3.4          | 2.8          |
| 0.150     | 3.4       | 0.1            | 2013 Nov 08 | MWA         | 3.2          | 2.6          |
| 0.158     | 3.3       | 0.1            | 2013 Nov 08 | MWA         | 3.1          | 2.5          |
| 0.166     | 3.1       | 0.1            | 2013 Nov 08 | MWA         | 3.0          | 2.4          |
| 0.174     | 3.0       | 0.1            | 2013 Nov 08 | MWA         | 2.8          | 2.3          |
| 0.181     | 2.9       | 0.1            | 2013 Nov 08 | MWA         | 2.7          | 2.2          |
| 0.189     | 2.8       | 0.1            | 2013 Nov 08 | MWA         | 2.6          | 2.1          |
| 0.197     | 2.7       | 0.1            | 2013 Nov 08 | MWA         | 2.5          | 2.1          |
| 0.204     | 2.5       | 0.1            | 2013 Nov 08 | MWA         | 2.4          | 2.0          |
| 0.212     | 2.4       | 0.1            | 2013 Nov 08 | MWA         | 2.3          | 1.9          |
| 0.219     | 2.4       | 0.1            | 2013 Nov 08 | MWA         | 2.3          | 1.8          |
| 0.227     | 2.3       | 0.1            | 2013 Nov 08 | MWA         | 2.2          | 1.7          |
| 1.375     | 0.58      | 0.05           | 2013 Aug 31 | ATCA        | 0.11         | 0.09         |
| 1.375     | 0.58      | 0.04           | 2014 Feb 04 | ATCA        | 0.08         | 0.07         |
| 2.351     | 0.43      | 0.02           | 2013 Aug 31 | ATCA        | 0.06         | 0.05         |
| 2.351     | 0.42      | 0.02           | 2014 Feb 04 | ATCA        | 0.05         | 0.04         |
| 4.788     | 0.28      | 0.01           | 2013 Aug 31 | ATCA        | 0.03         | 0.02         |
| 4.788     | 0.30      | 0.02           | 2014 Feb 04 | ATCA        | 0.03         | 0.02         |
| 8.642     | 0.18      | 0.03           | 2013 Aug 31 | ATCA        | 0.01         | 0.01         |
| 8.642     | 0.17      | 0.02           | 2014 Feb 04 | ATCA        | 0.01         | 0.01         |

et al. (submitted). In summary, Cotter (Offringa et al. 2015) was used to process the raw visibility data from the MWA observations, which involved averaging the data to 1 s time and 40 kHz frequency resolution, and excising radio frequency interference (RFI) using the AOFlagger algorithm (Offringa et al. 2012). An initial model of the sky for the five instantaneous observing bandwidths of 30.72 MHz was produced by observing bright calibrator sources. Hydra A was the calibrator source observed for the declination strip of the survey that included SNR 1987A. Such observations allowed initial amplitude and phase calibration solutions to be applied.

WSCLEAN (Offringa et al. 2014) was used for imaging as it appropriately accounts for wide-field u-term effects. WSCLEAN is a fast generic widefield imager that uses the w-stacking algorithm (Humphreys & Cornwell 2011) and the w-snapshot algorithm (Cornwell et al. 2012). Since SNR 1987A is unresolved at all MWA observing frequencies, baselines shorter than 60 m were excluded to minimise the contamination of large scale, diffuse structure present in the LMC, and a u,v-weighting scheme close to uniform weighting was chosen for imaging. In terms of the “Briggs” scheme this corresponds to a “robust” parameter of −1.0 (Briggs 1995). The snapshot observations were imaged across each 30.72 MHz band using multi-frequency synthesis down to the first negative clean component, without any major cycles. These images then went through a self-calibration loop, using the initial calibration images for quality control and to ensure the position of sources and the flux density of the image were consistent throughout the process. The RMS of the image was then measured and a new clean threshold was set to three times that RMS, which was between 200 to 40 mJy for 72 to 231 MHz, respectively. The observations were then divided into four 7.68-MHz sub-bands and jointly cleaned.

The Molonglo Reference Catalogue (MRC; Large et al. 1981, 1991) was used to set an initial flux density scale for the image and to correct for any right ascension dependent flux density scale errors due to the drift scan technique. An astrometric correction was also performed at this stage to fix bulk ionospheric distortions by using the positions of sources referenced in MRC. The snapshots for the entire observed declination strip were then mosaicked, with each snapshot weighted by the square of the primary beam response.

Finally, the residual declination dependence in the flux density scale, due to uncertainties in the primary beam model, was corrected. This was done by comparing the measured flux density in the mosaics for isolated, unresolved sources above 8σ of the noise floor to that predicted by their radio spectra using the 74 MHz Very Large Array Low-Frequency Sky Survey Redux (VLSSr; Lane et al. 2014), 408 MHz MRC, and the 1.4 GHz NRAO VLA Sky Survey (NVSS; Condon et al. 1998). This correction method places the flux density measurements on the Baars et al. (1977) flux density scale and dominates the uncertainty in the flux density measurements. The flux density calibration is accurate to 8%, as assessed by comparing the MWA flux densities at 150 MHz and 230 MHz to the 150 MHz TGSS-ADR1 survey (Intema et al. 2016) and Jansky Very Large Array (JVLA) P-band (230-450 MHz) observations of compact, non-variable sources (Hurley-Walker et al., submitted).

We convolved the appropriate synthesised beam at each sub-band frequency to characterise the flux density of all the sources within two degrees of the centre of the LMC for each of the 20 sub-band images. The sub-band image at 200-208 MHz, with SNR 1987A highlighted, is shown in Figure 1.

The background emission and noise properties of the individual sub-band images were measured using the backgrounding tool Background And Noise Estimator (BANE)\(^1\). BANE defines the background to be the mean of the pixel distribution, and the noise to be the variance about this mean. BANE was designed to quickly and accurately treat some of the unique problems of estimating the background and noise properties of radio images. It utilises two main techniques to reduce the compute time, whilst retaining a high level of accuracy. Firstly, since radio images can have a high level of correlation between adjacent pixels, BANE calculates the mean and variance on a sparse grid

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\(^1\) https://github.com/PaulHancock/Aegean/wiki/BANE

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of pixels and then interpolates to give the final background and noise images. Secondly, BANE uses sigma-clipping on the pixel distribution to avoid contamination from source pixels.

BANE calculated the background emission of the MWA images to vary between $\sim0.7$ Jy/beam to $\sim0.1$ Jy/beam for 72 to 231 MHz, respectively. The background and noise properties were then used by the source finding and characterisation program AEGERAN v1.9.6 (Hancock et al. 2012) to accurately identify and measure the flux density of the sources in the images. SNR 1987A was unresolved in all the subband images, so the flux density measurements were calculated by AEGERAN by fitting a Gaussian, convolved with the synthesised beam, to the source position.

At the lowest four frequencies, the synthesised beam becomes large enough to cause some blending of the Honeycomb nebula (Chu et al. 1995) and a background galaxy (Ball et al. 2001) with SNR 1987A, shown to the south-east of SNR 1987A in the inset of Figure 1. We estimate the upper limit of the contamination at these frequencies by extrapolating the spectra of the Honeycomb nebula and the background galaxy from a fit above the lowest four frequencies of the MWA data. This results in larger uncertainties for the flux density measurements between 72 and 103 MHz of SNR 1987A.

2.2 ATCA Observations and Data Reduction

SNR 1987A was observed as part of the ongoing ATCA monitoring campaign (project C015, PI Staveley-Smith) on 2013 August 31 and 2014 February 4 in array configurations 1.5A and 6D, respectively. The observations were conducted using the Compact Array Broadband Backend (CABB; Wilson et al. 2011) system, providing an instantaneous 2 GHz bandwidth, for both linear polarisations, at central frequencies of 2.1 GHz, 5.5 GHz and 9.0 GHz. For both observations PKS B1934-638 was used for gain and bandpass calibration and to set the flux density scale. PKS B0454-810, PKS B0407-658 and PKS B0530-727 were the secondary calibration and to set the flux density scale. PKS B0454-810, PKS B0407-658 and PKS B0530-727 were the secondary calibrators used for phase calibration. The total integration time on SNR 1987A in the August and February observations was approximately seven and six hours, respectively.

The data reduction process we applied is outlined by Zanardo et al. (2010). In summary, the data for both observations were reduced using the MIRIAD software package (Sault et al. 1995), with known regions of RFI and lower sensitivity in the CABB system initially flagged. The excision of RFI was conducted using the automatic flagging option in pgflag and manually with blflag. Since the LMC is a crowded field with many bright sources nearby SNR 1987A, only baselines longer than 3 k, where $i$ is the observing wavelength, were used to form images. To be consistent with pre-CABB monitoring data, the 2 GHz instantaneous bandwidth was split into four sub-bands with 128 MHz bandwidth, centred at 1.4, 2.4, 4.8 and 8.6 GHz. Gain calibration was performed on each sub-band independently. A self-calibration loop was conducted at this stage using a preliminary model generated by cleaning an image with a small number of iterations, with deeper cleaning conducted after the self-calibration loop was complete. The flux densities were measured by integrating a Gaussian fit to the emission region at 1.4 and 2.4 GHz, and by integrating over a polygonal region at 4.8 and 8.6 GHz.

3 RESULTS

We present the spectral energy distribution of SNR 1987A from 72 MHz to 8.64 GHz in Figure 2, plotted using the values reported in Table 1. Applying the Bayesian model inference routine outlined in Callingham et al. (2015), different emission and absorption models were fit to find the model that best described the spectrum and to test for any evidence of a spectral turnover or broad spectral curvature. This fitting method assumes that the flux density measurements are Gaussian and the ATCA data points are independent. The known correlation in the MWA flux measurements (Hurley-Walker et al., submitted) was approximated by a Matérn covariance function (Rasmussen & Williams 2006), which produces a stronger correlation between flux density measurements close in frequency space than further away. The Bayesian evidence $Z$ for each fit was calculated using the algorithm MultiNest (Feroz et al. 2013), which is an implementation of nested sampling. Uniform priors for each model parameter in a fit were utilised, allowing direct comparison to least-squares goodness-of-fit tests. While the spectral index of SNR 1987A has been gradually flattening with time (Zanardo et al. 2010), the data were simultaneously fit since the ATCA observations were almost equally spaced before and after the MWA observation. While the

![Figure 1](image-url)
flattening of the spectral index is small over the time between the ATCA and MWA observations (± 0.005), fitting the data simultaneously minimises any impact of variability.

The physically motivated models investigated included non-thermal synchrotron emission from relativistic electrons at the forward shock front, and homogeneous free-free absorption (Mezger & Henderson 1967) caused by the ionised circumstellar material swept up by the shock front. The homogeneous free-free absorption model includes attenuation of the underlying non-thermal synchrotron radiation by an ionised screen internal or external to the emitting electrons. We found the best fitting model to be the non-thermal synchrotron emission of the form:

\[ S_\nu = a \left( \frac{\nu}{1 \text{GHz}} \right)^\alpha, \]

where \( a \), in Jy, characterises the amplitude of the synchrotron spectrum, \( \alpha \) is the synchrotron spectral index, and \( S_\nu \) is the flux density at frequency \( \nu \), in GHz. The best fit of this model requires \( a = -0.74 \pm 0.02 \) and \( a = 0.82 \pm 0.01 \) Jy. The fit is plotted in Figure 2 and has a log evidence \( \Delta \) value of 8.32 ± 0.02, or a reduced \( \chi^2 \)-value of 0.84, calculated using 25 degrees of freedom. This spectral index is somewhat steeper, but still consistent, with what is expected from the higher frequency ATCA data and leads to a shock compression ratio of \( \sigma_s = 3.02 \pm 0.04 \), consistent with the range of compression ratios derived for SNR 1987A between 1.4 and 44 GHz (Berezhko & Ksenofontov 2006; Zanardo et al. 2010, 2014). This low compression factor implies the shock is still in the adiabatic phase and that sub-diffusive shock acceleration, without cosmic-ray feedback, is present.

While the spectrum of SNR 1987A is best described by a non-thermal power-law, we also fit an extrinsic free-free absorption model to place an upper limit on the optical depth. Assuming the ionised material is not mixed with the relativistic electrons that are producing the non-thermal spectrum, a spectrum with a peak below 72 MHz is characterised as

\[ S_\nu = a \left( \frac{\nu}{0.072 \text{GHz}} \right)^\alpha \exp \left[ -\tau_{72} \left( \frac{\nu}{0.072 \text{GHz}} \right)^{-2.1} \right], \]

where \( \tau_{72} \) is the free-free optical depth at the reference frequency of 72 MHz. The fit to the spectrum requires \( \tau_{72} \leq 0.1 \) at 3σ.

Model selection can be performed based on the difference between the log evidence of two models \( \Delta \ln(Z) = \ln(Z_2) - \ln(Z_1) \), where \( \Delta \ln(Z) \geq 3 \) is taken as strong evidence that the second model is favoured over the first (Kass & Raftery 1995). The difference in the log evidence value between the free-free absorption fits and synchrotron radiation fit were found to be greater than 200, implying that the non-thermal synchrotron emission is strongly favoured over both internal and external free-free absorption. Non-physically motivated models, such as quadratic and quartic curves, were also fit to the spectrum to test for spectral curvature. The difference in evidence between these non-physical models and the synchrotron spectrum was always greater than 165, suggesting there is no statistical evidence of curvature in the spectrum of SNR 1987A. This implies that if a turnover exists in the spectrum of SNR 1987A, it has to occur at a frequency lower than 72 MHz.

Note that we excluded synchrotron self-absorption as a potential absorption mechanism as it was shown by Chevalier (1998) that synchrotron self-absorptionceased almost immediately after the prompt burst. Additionally, the Razin-Tsytovich effect (Tsytovich 1951; Razin 1957) is unlikely to be contributing to the absorption because it would require the density of the radiating region to be nearly two orders of magnitude larger than the postshock density, which is greater than expected for the synchrotron emitting region of SNR 1987A (Chevalier 1982; Chevalier & Dwarkadas 1995). Therefore, free-free absorption by an ionised circumstellar material is the only plausible mechanism for a spectral turnover, considering the observations reported in this paper were conducted over 9640 days since SNR 1987A occurred.

4 DISCUSSION

The MWA observation of SNR 1987A represents the lowest frequency detection of SNR 1987A, over an order of magnitude lower than the previous lowest frequency observations at 843 MHz. This allows us to place a limit on the density of ionised material present around the shock producing the synchrotron emission. Since the best fitting model is a non-thermal power-law, if a turnover is present in the spectrum, it has to occur at or below a frequency of 72 MHz. The medium responsible for the ionised material would likely be the surrounding HII and “hourglass” regions deposited by the expansion of SNR 1987A progenitor’s wind during its red supergiant phase (Chevalier & Dwarkadas 1995). This is because the forward shock front has swept around the dense equatorial ring ~1000 days before the observations presented in this paper were made (Potter et al. 2014).

Note that our observations are dominated by the emission from the expanding synchrotron emitting shell produced from the interaction of the forward shock with the circumstellar environment (Chevalier 1982). The radio emission interior to this shell is not detected since the density in this region is too low for efficient particle acceleration environments to form, and any emission is absorbed by the dense material that exists between the reverse shock and the interior of the supernova (Lundqvist 1999; Chevalier & Fransson 2003; Potter et al. 2014). Therefore, our observations are only sensitive to absorption by the circumstellar material deposited by the progenitor, rather than intrinsic absorption by the supernova ejecta.

To place an upper limit on the emission measure \( EM = \int f n_e^2 \, dl \), we re-parametrise the free-free optical depth from Equation 2 in terms of \( T_e \) in K, free electron density \( n_e \) in \( \text{cm}^{-3} \), the path length \( l \) in pc, and filling factor of the ionised gas \( f \) as

\[ \tau_f \approx 8.24 \times 10^{-5} a(\alpha T_e)^{\frac{1}{2}} \exp^{-2.1 T_e^{-1.35}} \int f n_e^2 \, dl. \]

The Gaunt factor \( a(T_e, \nu) \approx 1 \) for the range of astrophysical quantities investigated in this study (Osterbrock 1989).

The form of Equation 3 is derived assuming the HII region is composed of hydrogenic gas, implying an atomic number of ~1, and the number density of electrons and ions will be equal since the HII region will be fully ionised.
from the ultraviolet (UV) radiation emitted from the supernova event. Emission line measurements and environmental simulations suggest the electron temperature of the H\textsc{ii} and “hourglass” regions will be $\sim 6 \times 10^4$ K after the UV flash (Lundqvist & Fransson 1991; Lundqvist 1999; Sugerman et al. 2005) and before the forward shock of the supernova passes through (Chevalier & Dwarkadas 1995; Potter et al. 2014). Substituting this information, and the fact $\tau_{72} \leq 0.1$, into Equation 3 places an upper limit on the emission measure of $EM \leq 13,000 \text{ cm}^{-6}\text{pc}$.

While there is ambiguity about whether the turnover in the spectrum of Galactic SNRs is intrinsic or due to the ionised interstellar medium of the Milky Way (Kassim 1989), the path length of a photon from SNR 1987A through the interstellar medium of the LMC is significantly shorter than most Galactic SNRs. For example, since the electron density of the LMC near the position of SNR 1987A is measured to be $n_e \sim 0.08 \text{ cm}^{-3}$ (Kim et al. 2003; Cox et al. 2006) and the distance of SNR 1987A from the edge of the LMC is $\sim 1 \text{ kpc}$ (Xu et al. 1995; Sugerman et al. 2005), the interstellar medium of the LMC has an emission measure $EM \leq 6 \text{ cm}^{-6}\text{pc}$. Hence, any turnover in the spectrum of SNR 1987A would be completely dominated by absorption from material associated with the system of SNR 1987A.

The emission measure also allows us to place an upper limit on the electron density in the red supergiant wind. For a radio photon emitted from the forward shock it will have an equivalent path length $l \sim 1 \text{ pc}$, based on the current position of the forward shock and the total size of the H\textsc{ii} and “hourglass” region, assuming the progenitor was in the red supergiant phase for $\sim 5 \times 10^5 \text{ yr}$ (Blondin & Lundqvist 1993; Chevalier & Dwarkadas 1995; Potter et al. 2014). Provided the ionised material is distributed in a slab with a uniform density ($f = 1$), this produces an upper limit on the electron density $n_e = \sqrt{EM/f} \leq 110 \text{ cm}^{-3}$. While the filling factor of the H\textsc{ii} and “hourglass” region is unknown, any deviation from unity will be small (e.g. Lundqvist 1999; Ohnaka et al. 2008; Fransson et al. 2015), and will have a minimal impact on the electron density limit since dependency on the filling factor goes as $n_e \propto f^{-0.3}$.

An electron density $n_e \leq 110 \text{ cm}^{-3}$ is consistent with the limits placed from the detection of the prompt radio emission, as any circumstellar envelope must be relatively thin otherwise the prompt radio burst would not have been observed (Storey & Manchester 1987). Such an upper limit on the electron number density is also compatible with models of the X-ray emission from the supernova, which often require a electron density of $n_e \sim 90 \text{ cm}^{-3}$ (Borkowski et al. 1997; Park et al. 2002) in the H\textsc{ii} and “hourglass” region.

We can also estimate the density of the H\textsc{ii} and “hourglass” region from the mass loss the progenitor underwent when it was a red supergiant. The asymmetric wind profile from Blondin & Lundqvist (1993) has the environmental mass density $\rho$ described in terms of the mass loss rate of the red supergiant $M$, velocity of the red supergiant wind $v_w$, radius from centre of the system $r$, and the asymmetry parameter $A$ as

$$\rho(r, \theta) = \frac{3M}{(3 - A)4\pi r^2 v_w}(1 - A \cos^2 \theta),$$

where $\theta$ is the angle from the pole of the progenitor. The best fitting model from the two dimensional hydrodynamic simulations of Blondin & Lundqvist (1993) found $M = 2.0 \times 10^{-5} \text{ M}_\odot \text{ yr}^{-1}$, $v_w = 5 \text{ km s}^{-1}$ and $A = 0.95$. The

![Figure 2. Spectral energy distribution of SNR 1987A from 0.072 to 8.64 GHz. The MWA data points are plotted in black. The monitoring data from the ATCA for 2013 August 31 and 2014 February 4 are shown in blue and green, respectively. The best fit power-law model to all the data is presented in orange, with the shaded orange region representing the 1-$\sigma$ uncertainty on the model fit at the respective frequency. The $\chi^2$ values for the power-law fit to the data, which represent the residuals to the fit divided by the uncertainties in the flux density measurements, are displayed in the panel below the spectral energy distribution.](image-url)
asymmetry of the mass loss produces an equatorial density ratio of 20:1. The largest number density of electrons, and thus the most likely site of absorption, will occur just before the forward shock front, which at day 9640 is at $r \sim 0.4$ pc (Potter et al. 2014). In the equatorial plane this model predicts $n_e \approx 120$ cm$^{-3}$. This value is close to, but above, the limit we place based on the MWA observations of SNR 1987A.

Therefore, the number density of electrons derived from the model of Blondin & Lundqvist (1993), which is also used by Potter et al. (2014) to model the initial environment of the system, is marginally inconsistent with the upper limit placed by our observations. We note that the inconsistency between the derived and observed electron density is highly dependent on the value of $r$. To ensure our findings are robust, we chose a value of $r$ that was at the upper-limit of those calculated from the simulations of Potter et al. (2014) and the observations of Zanardo et al. (2014). Since we have used a conservatively large value of $r$, it is likely either the mass loss rate is too high and/or the red supergiant wind velocity is too low in the model of Blondin & Lundqvist (1993).

Since the mass loss rate and wind speed are degenerate, we can parametrise the optical depth in terms of the physical properties of the supernova shock to place a limit on the ratio of the progenitor’s mass loss rate and wind speed. Using the velocity of the forward shock $v_{\text{sh}}$, in units of $10^4$ km s$^{-1}$, and the time since the explosion $t$, in units of $10^5$ s, the ratio of the mass loss rate and velocity of the wind can be expressed as

$$\left(\frac{M_{\text{wind}}}{v_{\text{wind}}}\right)^2 = 0.25\nu^2\tau_s(v_{\text{sh}}t)^3,$$  \hspace{1cm} (5)

where the mass loss rate is in units of $10^{-5} M_\odot$ yr$^{-1}$, the velocity of the red supergiant wind is in units of 10 km s$^{-1}$, and the frequency is in units of GHz (Chevalier 1981, 1982). Since the observations reported in this paper were conducted $\approx 9640$ days since SN 1987A occurred, with $\tau_s \leq 0.1$, and $v_{\text{sh}} \sim 5000$ km s$^{-1}$ (Potter et al. 2014), it follows that $M_{\text{wind}}/v_{\text{wind}} \leq 2.2 M_\odot$ yr$^{-1}$ km$^{-3}$/s. Again, the mass loss rate and wind velocity derived by Blondin & Lundqvist (1993) are not consistent with our observations. Note that Equation 5 may lead to an overestimate of $M_{\text{wind}}/v_{\text{wind}}$ if the medium is found to be significantly clumpy (Chevalier & Fransson 2003).

Using optical and infrared observations of SNR 1987A, Sugerman et al. (2005) derived a mass loss rate of $M \sim 5 \times 10^{-8} M_\odot$ yr$^{-1}$, which is close to the median mass loss rate of the red supergiant population (Knapp & Morris 1985). Additionally, Koo & McKee (1992) suggest a more realistic wind velocity of $v_{\text{wind}} = 10$ km s$^{-1}$, corresponding to a “slow wind” expanding into a tenuous medium and becoming immediately radiative. Applying either, or both, of these values to Equation 5 provides a mass loss rate-wind velocity ratio consistent with our upper limit, and predicts a spectral turnover frequency between $\sim 5$ and 60 MHz.

Future observations of SNR 1987A at or below 50 MHz could be helpful in identifying the spectral turnover frequency and providing tighter constraints on the mass loss rate of the progenitor. The only telescope currently planned that could target SNR 1987A at 50 MHz is the low frequency array of the Square Kilometre Array (SKA1-Low; Dewdney et al. 2013; de Lera Acedo et al. 2015). However, assuming Equation 4 provides an accurate evolution of the circumstellar medium and that the turnover in the spectrum is currently $\sim 50$ MHz, we would predict a turnover frequency of $\sim 10$ MHz by the time SKA1-Low becomes operational in approximately 2023. Hence, it is possible that SKA1-Low will not provide better constraints on the spectral turnover than that presented in this paper.

Continual monitoring of SNR 1987A with the MWA will be useful in investigating the physical properties of the circumstellar medium and physics of diffusive shock acceleration. Gradual flattening of the spectral index, in line with higher frequency observations (Zanardo et al. 2010), will provide a more accurate measure of the strength of the magnetic field in the forward shock and the shock compression ratio (Berezhko & Ksenofontov 2006). Additionally, any observed steepening in the spectral index at low radio frequencies, relative to the high frequency observations, would be indicative of a re-acceleration of electrons by a central compact object (Zanardo et al. 2014). A decrease in the spectral index would suggest the interaction of the shock front with a denser circumstellar medium than currently predicted by mass loss models of the progenitor.

5 CONCLUSION

We have presented observations of SNR 1987A between 72 MHz and 8.4 GHz, with the MWA observations representing the lowest frequency observations of SNR 1987A to date. This large lever arm in frequency space has allowed us to probe the circumstellar environment of SNR 1987A and test different mass loss scenarios of the progenitor at an unprecedented level.

The radio spectrum of SNR 1987A does not show any deviation from a non-thermal power-law with a spectral index of $\alpha = -0.74 \pm 0.02$. Since free-free absorption has to cause a spectral turnover to occur below 72 MHz, we derived an upper limit on the optical depth $\tau_s \leq 0.1$, placing an upper limit on the emission measure of $\tau_s \leq 13,000$ cm$^{-6}$ pc and electron density of $n_e \leq 110$ cm$^{-3}$. These limits are consistent with limits determined from the detection of the prompt radio emission and X-ray spectra.

The mass loss rate or wind velocity, or both, derived from previous the hydrodynamic simulations were found to be too high to be consistent with our electron density upper limit. The mass loss rate of $M \sim 5 \times 10^{-8} M_\odot$ yr$^{-1}$ and the wind velocity of $v_{\text{wind}} = 10$ km s$^{-1}$, derived from optical data, are compatible with our observations. Therefore, we predict a current spectral turnover frequency between $\sim 5$ and 60 MHz. We conclude that while SKA1-Low will provide lower frequency observations than reported in this paper, due to the progression of the shock into a lower density circumstellar medium, it will be unlikely SKA1-Low will detect the spectral turnover once it is operational in approximately 2023.

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REFERENCES

Baars J. W. M., Genzel R., Pauliny-Toth I. I. K., Witzel A., 1977, A&A, 61, 99
Ball L., Crawford D. F., Hunstead R. W., Klappe I., McIntyre V. J., 2001, ApJ, 549, 599
Berezhko E. G., Ksenofontov L. T., 2006, ApJ, 650, L59
Blondin J. M., Lundqvist P., 1993, ApJ, 405, 337
Borkowski K. J., Blondin J. M., McCray R., 1997, ApJ, 477, 281
Briggs D. S., 1995, PhD thesis, New Mexico Institute of Mining and Technology
Brogan C. L., Lazio T. J., Kassim N. E., Dyer K. K., 2005, AJ, 130, 148
Callingham J. R., et al., 2015, ApJ, 809, 168
Chevalier R. A., 1981, ApJ, 251, 259
Chevalier R. A., 1982, ApJ, 259, 302
Chevalier R. A., 1990, in Kassim N. E., Weiler K. W., eds, Lecture Notes in Physics, Berlin Springer Verlag Vol. 362, Low Frequency Astrophysics from Space, pp 130–137, doi:10.1007/3-540-52891-1_17
Chevalier R. A., 1998, ApJ, 490, 810
Chevalier R. A., Dwarkadas V. V., 1995, ApJ, 452, L45
Chevalier R. A., Fransson C., 2003, in Weiler K., ed., Lecture Notes in Physics, Berlin Springer Verlag Vol. 598, Supernovae and Gamma-Ray Bursters, pp 171–194 (arXiv:astro-ph/0110060), doi:10.1007/3-540-45863-8_40
Chu Y.-H., Dickel J. R., Staveley-Smith L., Osterberg J., Smith R. C., 1995, AJ, 109, 1729
Collins T. B., Frank A., Bjorkman J. E., Livio M., 1999, ApJ, 512, 322
Condon J. L., Cotton W. D., Green R. F., Yin Q. F., Perley R. A., Taylor G. B., Broderick J. J., 1998, AJ, 115, 1693
Conwell T. J., von Ormondt M. A., Humphreys B., 2012, in Image Reconstruction from Incomplete Data VII. p. 85000L (arXiv:1207.5881), doi:10.1117/12.929326
Cox N. L. J., Cordiner M. A., Cami J., Foning B. H., Sarre P. J., Kaper L., Ehrenfreund P., 2006, A&A, 447, 991
Crofts A. P., Heathcote S. R., 1991, Nature, 350, 683
Crofts A. P. S., Kunkel W. E., Heathcote S. R., 1995, ApJ, 438, 724
DeLaney T., Kassim N. E., Rudnick L., Perley R. A., 2014, ApJ, 785, 7
Dewdney P. E., Turner W., Millenaar R., McCool R., Lazio J., Cornwell T. J., 2013, SKA-TEL-SKO-DD-001
Fedor F., Hobson M. P., Cameron E., Pettitt A. N., 2013, arXiv:1306.2144.
Fransson C., et al., 2015, ApJ, 806, L19
Hancock P. J., Murphy T., Gaensler B. M., Hopkins A., Curran J. R., 2012, MNRAS, 422, 1812
Humphreys B., Cornell T. J., 2011, SKA MEMO 132, available at: https://www.skatelescope.org/uploaded/59116_132_Memo_Humphreys.pdf
Intema H. T., Jagannathan P., Mooley K. P., Frail D. A., 2016, preprint, (arXiv:1603.04368)
Kass R. E., Rafterty A. E., 1995, Journal of the American Statistical Association, 90, 773
Kassim N. E., 1989, ApJ, 347, 915
Kassim N. E., Perley R. A., Dwarakanath K. S., Erickson W. C., 1995, ApJ, 455, L59
Kavanagh P. J., Sasaki M., Boszetto L. M., Points S. D., Filipović M. D., Maggi P., Haberl F., Crawford E. J., 2015, A&A, 583, A121
Kim S., Staveley-Smith L., Dupita M. A., Sault R. J., Freeman K. C., Lee Y., Chu Y.-H., 2003, ApJS, 148, 473
Knapp G. R., Morris M., 1985, ApJ, 292, 640
Koo B.-C., McCree C. F., 1992, ApJ, 388, 93
Koshiha M., et al., 1987, IAU Circ., 4338
Kunkel W., et al., 1987, IAU Circ., 4316
Lacey C. K., Lazio T. J. W., Kassim N. E., Duric N., Briggs D. S., Dyer K. K., 2001, ApJ, 559, 954
Lane W. M., Cotton W. D., van Velzen S., Clarke T. E., Kassim N. E., Helmboldt J. F., Lazio T. J. W., Cohen A. S., 2014, MNRAS, 440, 327
Large M. I., Mills B. Y., Little A. G., Crawford D. F., Sutton M. J., 1981, MNRAS, 194, 693
Large M. I., Cram L. E., Burgess A. M., 1991, The Observatory, 111, 72
Lundqvist P., 1999, ApJ, 511, 389
Lundqvist P., Fransson C., 1991, ApJ, 380, 575
Mezger P. G., Henderson A. P., 1967, ApJ, 147, 471
Mills B. Y., Turtle A. J., Little A. G., Durnid J. M., 1984, Australian Journal of Physics, 37, 321
Offringa A. R., van de Gonde J. J., Roerdink B. T. M., 2012, A&A, 539, A95
Offringa A. R., et al., 2014, MNRAS, 444, 606
Offringa A. R., et al., 2015, Publ. Astron. Soc. Australia, 32, 8
Ohsaka K., Driebe T., Hofmann K.-H., Weigelt G., Wittkowski M., 2008, A&A, 484, 371
Osterbrock D. E., 1989, Astrophysics of gaseous nebulae and active galactic nuclei
Park S., Burrows D. N., Garmire G. P., Nousek J. A., McCray R., Michael E., Zhekov S., 2002, ApJ, 567, 314
Plait P. C., Lundqvist P., Chevalier R. A., Kirshner R. P., 1995, ApJ, 439, 730
Podsiadlowski P., Joss P. C., 1989, in Years After: Supernovae and Gamma-Ray Bursters. pp 125–194
Podsiadlowski P., Morris T. S., Ivanova N., 2007, in Imm-
ler S., Weiler K., McCray R., eds, American Institute of Physics Conference Series Vol. 937, Supernova 1987A: 20 Years After: Supernovae and Gamma-Ray Bursters. pp 125–333, doi:10.1063/1.3682893
Potter T. M., Staveley-Smith L., Reville B., Ng C.-Y., Bicknell G. V., Sutherland R. S., Wagner A. Y., 2014, ApJ, 794, 174
Rasmussen C., Williams C., 2006, Gaussian Processes for Machine Learning. Adaptive Computation and Machine Learning, MIT Press, Cambridge, MA, USA
Razin V. A., 1957, Dissertation, Gorki State University
Sault R. J., Teuben P. J., Wright M. C. H., 1995, in Shaw R. A., Payne H. E., Hayes J. J. E., eds, Astronomical Society of the

MNRAS 000, 1–9 (2016)
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Pacific Conference Series Vol. 77, Astronomical Data Analysis Software and Systems IV, p. 433 (arXiv:astro-ph/0612759)

Slee O. B., 1995, Australian Journal of Physics, 48, 143

Smith N., 2007, AJ, 133, 1034

Staveley-Smith L., Briggs D. S., Rowe A. C. H., Manchester R. N., Reynolds J. E., Tzioumis A. K., Kesteven M. J., 1993, Nature, 366, 136

Storey M. C., Manchester R. N., 1987, Nature, 329, 421

Sugarman B. E. K., Crotts A. P. S., Kunkel W. E., Heathcote S. R., Lawrence S. S., 2005, ApJ, 627, 888

Svoboda R., et al., 1987, IAU Circ., 4340

Tingay S. J., et al., 2013, PASA, 30, 7

Tsytovich V. N., 1951, Vesti. Mosk. Univ., 11, 27

Turtle A. J., et al., 1987, Nature, 327, 38

Wayth R. B., et al., 2015, Publ. Astron. Soc. Australia, 32, 25

Wilson W. E., et al., 2011, MNRAS, 416, 832

Woosley S. E., Pinto P. A., Martin P. G., Weaver T. A., 1987, ApJ, 318, 664

Xu J., Crotts A. P. S., Kunkel W. E., 1995, ApJ, 451, 806

Zanardo G., et al., 2010, ApJ, 710, 1515

Zanardo G., et al., 2014, ApJ, 796, 82

de Lera Acedo E., Razavi-Ghods N., Troop N., Drought N., Faulkner A. J., 2015, Experimental Astronomy, 39, 567

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