



A radio continuum study of NGC 2082

J.C.F. Balzan¹ · M.D. Filipović¹ · S. Dai^{1,2} · R.Z.E. Alsaberi¹ · L. Barnes¹

Received: 8 April 2022 / Accepted: 22 May 2022 / Published online: 9 June 2022
© The Author(s) 2022

Abstract

We present radio continuum observations of NGC 2082 using ASKAP, ATCA and Parkes telescopes from 888 MHz to 9000 MHz. Some 20 arcsec from the centre of this nearby spiral galaxy, we discovered a bright and compact radio source, J054149.24–641813.7, of unknown origin. To constrain the nature of J054149.24–641813.7, we searched for transient events with the Ultra-Wideband Low Parkes receiver, and compare its luminosity and spectral index to various nearby supernova remnants (SNRs), and fast radio burst (FRB) local environments. Its radio spectral index is flat ($\alpha = 0.02 \pm 0.09$), which is unlikely to be either an SNR or pulsar. No transient events were detected with the Parkes telescope over three days of observations, and our calculations show J054149.24–641813.7 is two orders of magnitude less luminous than the persistent radio sources associated with FRB 121102 and 190520B. We find that the probability of finding such a source behind NGC 2082 is $P = 1.2\%$, and conclude that the most likely origin for J054149.24–641813.7 is a background quasar or radio galaxy.

Keywords Radio continuum: galaxies · Galaxies: spiral · Galaxies: ISM

1 Introduction

In the absence of an active galactic nucleus (AGN), a spiral galaxy's radio emission primarily derives from non-thermal synchrotron radiation from supernova remnants (SNRs), and thermal bremsstrahlung from HII regions (Condon 1992; Filipović and Tothill 2021b,a). Thus, deep and wide radio surveys from the new generation of radio telescopes such as the Australian Square Kilometre Array Pathfinder (ASKAP) and MeerKAT can shed important light on the processes by which star formation shapes the interstellar medium (ISM).

NGC 2082 is a G-type spiral galaxy (of SB(r)b morphology) in the Dorado constellation. It has an absolute B-band magnitude of $M_B = 12.79$ (Lauberts and Valentijn 1989), a diameter of 10.16 kpc, and is located at a distance of 18.5 Mpc (Olivares E. et al. 2010) and redshift $z = 0.00395$. Unlike some other galaxies in the Dorado constellation (e.g. NGC 1566), NGC 2082 remains poorly studied, with its most notable feature being a type-II supernova, SN1992ba (Evans and Phillips 1992).

Here, we study the radio properties of NGC 2082 using ASKAP, Australia Telescope Compact Array (ATCA) and Parkes radio telescope observations. We will also draw on Hubble Space Telescope (HST) observations. Section 2 presents our observations and data analysis of NGC 2082. Section 3 gives our results and discussion, and conclusions are presented in Sect. 4.

2 Observations and data

NGC 2082 has been observed in the ASKAP–EMU 888-MHz radio continuum survey of the Large Magellanic Cloud (LMC; Pennock et al. 2021; Filipović et al. 2022), as well as in the ATCA 20-cm mosaic survey (Filipović et al. 2021). We have also made new observations from Parkes radio telescope, and obtained new and archival data from ATCA (pre-CABB) and the HST.

✉ J.C.F. Balzan
jbalzan.astro@gmail.com

M.D. Filipović
M.Filipovic@westernsydney.edu.au

S. Dai
Shi.Dai@westernsydney.edu.au

R.Z.E. Alsaberi
19158264@student.westernsydney.edu.au

L. Barnes
l.barnes@westernsydney.edu.au

¹ Western Sydney University, Locked Bag 1797, Penrith South DC, NSW 1797, Australia

² CSIRO Astronomy and Space Sciences, Australia Telescope National Facility, PO Box 76, Epping, NSW 1710, Australia

2.1 Australian telescope compact array

2.1.1 CABB

We observed NGC 2082 on November 30th 2019 using the Australian Telescope Compact Array (ATCA) (project code C3275 with 1.5C array configuration). The observations were carried out in ‘snap-shot’ mode, with 1 hour of integration over a 12-hour period as a minimum. We used the Compact Array Broadband Backend (CABB) (with 2048 MHz bandwidth), centred at a) wavelengths of 3/6 cm ($\nu = 4500\text{--}6500$ and $8000\text{--}10\,000$ MHz), totalling 43.2 minutes of integration and, b) 13 cm ($\nu = 2100$ MHz), totalling 43.2 minutes of integration. The primary calibrator (flux) was PKS B1934–638 and the secondary calibrator (phase) was PKS B0530–727.

The MIRIAD¹ (Sault et al. 1995) and KARMA² (Gooch 1995) software packages were used for reduction and analysis. Imaging was completed using the multi-frequency synthesis INVERT task with natural Briggs weighting (robust=0 for all images), and a beam size of 4.5×4.1 arcsec, 1.9×1.8 arcsec and 1.3×1.0 arcsec for 2100, 5500 and 9000 MHz images, respectively. The MFCLEAN and RESTOR algorithms were used to deconvolve the images, with primary-beam correction applied using the LINMOS task. We follow the same process with Stokes Q and U parameters to produce polarisation maps, except with a beam size of 5×5 arcsec (see Sect. 3.2 below).

2.1.2 Pre-CABB

We analysed archival³ ATCA data (project code C466 with 6A array configuration) from 16th November 1995. The observations used a pre-CABB receiver (with 128 MHz bandwidth), centred at wavelengths of 3/6 cm (4800 and 8640 MHz) totalling 48 minutes of integration. The primary calibrator (flux) was PKS B1934–638 and the secondary calibrator (phase) was PKS B0355–483.

2.2 Australian square kilometre array pathfinder

NGC 2082 was observed serendipitously in the ASKAP-EMU radio continuum survey of the Large Magellanic Cloud (Pennock et al. 2021), at the edge of the 120-deg²

¹<http://www.atnf.csiro.au/computing/software/miriad/>

²<http://www.atnf.csiro.au/computing/software/karma/>

³Australia Telescope Online Archive (ATOA), hosted by the Australia Telescope National Facility (ATNF): <https://atoa.atnf.csiro.au>

field. This survey was performed at 888 MHz with a 288-MHz bandwidth and a 13.9×12.1 arcsec beam size.

2.3 Parkes radio telescope

We observed NGC 2082 on June 14th, 15th and 18th 2021 with the Parkes radio telescope (project code PX075) using the Ultra-Wideband-Low (UWL) receiver (Hobbs et al. 2020), which delivers radio-frequency coverage from 704 MHz to 4032 MHz. All observations were pointed at J054149.24–641813.7 and executed using the transient search mode where data are recorded with 2-bit sampling every 64 μ s in each of the 0.125-MHz wide frequency channels (26 624 channels across the whole band).

The full UWL band was split into multiple 512-MHz sub-bands for the search of bursts. The search was performed using the pulsar-searching software package PRESTO (Ransom 2001). Radio-frequency interferences (RFI) were identified and marked using the PRESTO routine RFIFIND with a 1-s integration time. To determine the optimal dispersion measure (DM) steps of the search, we used the DDPLAN.PY routine of PRESTO for a DM range of 200 to 3000 cm^{-3} pc. Data were then dedispersed at each of the trial DMs using the PREPDATA routine with RFI removal based on the mask file produced by RFIFIND.

Single-pulse candidates with a signal-to-noise ratio larger than seven were identified using the SINGLE_PULSE_SEARCH.PY routine for each dedispersed time series and for different boxcar filtering parameters (from 1 to 300 samples). Burst candidates were manually examined.

2.4 Hubble space telescope

NGC 2082 was first imaged by the Hubble Space Telescope in 1997, following the type-II supernova SN1992ba (Evans and Phillips 1992), revealing a bright, face-on spiral galaxy (Fig. 1). Figure 1 is a 3-colour image created with APLpy (Robitaille and Bressert 2012), using archival HST data⁴ (Carollo et al. 2002), where the red channel uses I-band data (F814W filter), the blue channel uses B-band data (F435W filter), and the green channel is pseudo-green that has been constructed by stacking the red and blue channels (B+I-band). No detection of SN1992ba is reported; it cannot be seen in any of these images.

⁴Based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CAD/C/NRC/CSA).

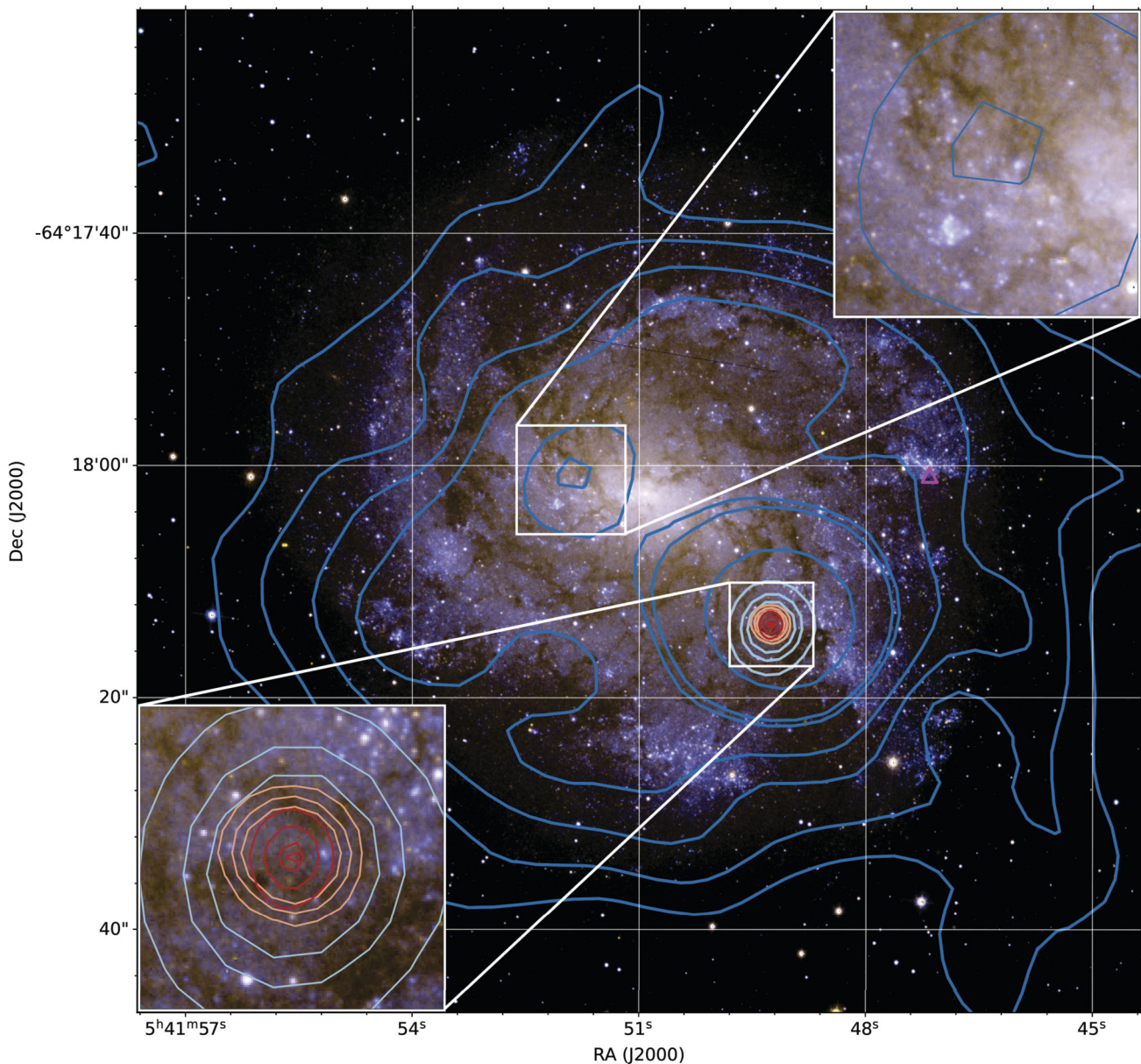


Fig. 1 3-colour HST image of NGC 2082 overlaid with ASKAP and ATCA contours. The blue contours are ASKAP 888 MHz (0.3, 0.5, 0.7, 0.9, 1.3, 1.4 and 2.1 mJy beam^{-1}), and the light-blue, orange and red contours are ATCA 2100 MHz (0.4, 1.0 and 1.5 mJy beam^{-1}), 5500 MHz (0.5, 1.0 and 1.5 mJy beam^{-1}), and 9000 MHz (0.4346, 1.5198, 3.0 and 3.4 mJy beam^{-1}), respectively. The inset image in the

bottom-left provides a zoom-in of J054149.24–641813.7, showing the absence of any optical counterpart. The subplot in the top-right provides a zoom-in of a 888-MHz flux density peak of 1.3 mJy beam^{-1} , almost directly opposite J054149.24–641813.7. The magenta triangle denotes the position of SN1992ba

3 Results and discussion

A striking feature in all our radio images of NGC 2082 is a strong point radio source (J054149.24–641813.7) positioned 20 arcsec from the galaxy centre, as seen in the bottom-left image of Fig. 1 by the ATCA contours. We also note no detection of SN1992ba in any of our images. The 9000-MHz ATCA observations, with our highest resolution, shows an unresolved point radio source, regardless

of the parameters used in the data reduction. The top-right subplot in Fig. 1 provides a better look at an 888-MHz emission peak flux density of 0.0013 Jy beam^{-1} opposing J054149.24–641813.7, and also away from the centre of the galaxy. It is unlikely that the two radio sources are related. Finally, we note HST observations with F435W and F814W filters show no optical counterparts to either source, and there are no counterparts at other wavelengths.

Table 1 The radio flux densities of NGC 2082's extended radio emission and radio point source J054149.24–641813.7 (point source). A '—' represents a non-detection

Freq. & Telescope (MHz)	S _{NGC 2082} (mJy)	S _{point source} (mJy)
888 & ASKAP	13.4 ± 1.3	3.5 ± 0.4
2100 & ATCA CABB	11.2 ± 1.1	2.7 ± 0.3
4800 & ATCA Pre-CABB	—	4.0 ± 0.4
5500 & ATCA CABB	—	4.0 ± 0.4
8640 & ATCA Pre-CABB	—	3.0 ± 0.3
9000 & ATCA CABB	—	3.6 ± 0.4
$\alpha \pm \Delta\alpha$	−0.15 ± 0.23	+0.02 ± 0.09

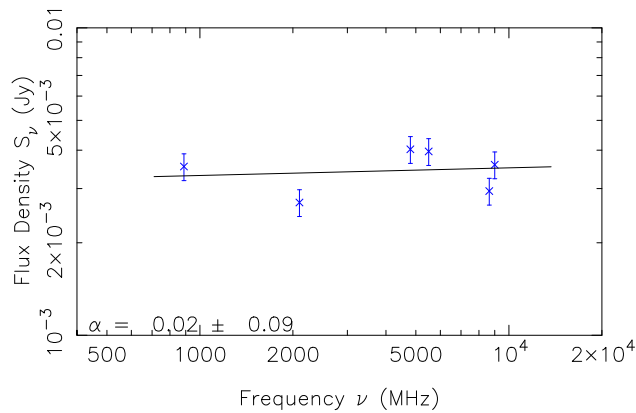


Fig. 2 The spectral index of J054149.24–641813.7 ($\alpha = 0.02 \pm 0.09$) with assumed 10% error bars, based on the measured flux densities from Table 1

3.1 Spectral index

In Table 1 we show the flux densities of J054149.24–641813.7, measured using CARTA⁵ and treated as a point source. We assume that the flux-density errors are <10 per cent. We estimate a flat radio spectral index of $\alpha = +0.02 \pm 0.09$, suggesting that the emission is predominantly of thermal origin if the source is located in NGC 2082 (Fig. 2). Such a flat spectral index would be very unusual among SNRs and radio pulsar sources (Urošević 2014; Bates et al. 2013; Dai et al. 2015) unless this source is an unresolved pulsar wind nebulae (PWN). However, a background galaxy (quasar) could explain this radio spectrum (see Sect. 3.5).

To measure the flux densities of NGC 2082's entire extended emission, we use the method described in Hurley-Walker et al. (2019b) and Hurley-Walker et al. (2019a), which includes careful region selection that also excludes J054149.24–641813.7. We measure reliable NGC 2082 flux densities at two frequencies (888 and 2100 MHz; Table 1), which allows us to estimate the spectral index of $\alpha = -0.15 \pm 0.23$. This flat radio spectral index is unusual for

spiral galaxies, Gioia et al. (1982), but consistent with thermal emission from HII regions across NGC 2082. As the nucleus of NGC 2082 does not show any radio compact source or emission above 0.1 mJy beam⁻¹, we suggest this might account for the unusually flat radio spectral index.

3.2 Polarisation

We also investigate if any polarisation from J054149.24–641813.7 or NGC 2082 can be detected in our ATCA images. The fractional linear polarisation (P) of NGC 2082 was calculated using the equation:

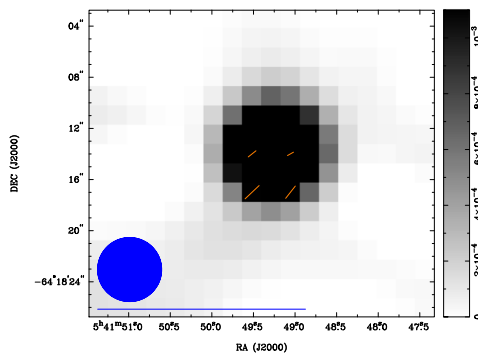
$$P = \frac{\sqrt{S_Q^2 + S_U^2}}{S_I}, \quad (1)$$

where P is the mean fractional linear polarisation, S_Q , S_U and S_I are integrated intensities for the Q , U and I Stokes parameters, respectively. We calculate $P_{5500 \text{ MHz}} = 6 \pm 2\%$ (see Fig. 3a) and $P_{9000 \text{ MHz}} = 8 \pm 4\%$ (see Fig. 3c). Their associated polarisation intensity maps are seen in Figs. 3b and 3d, respectively. This weak polarisation associated with J054149.24–641813.7 is most likely explained if the source is of background origin (see Sect. 3.5).

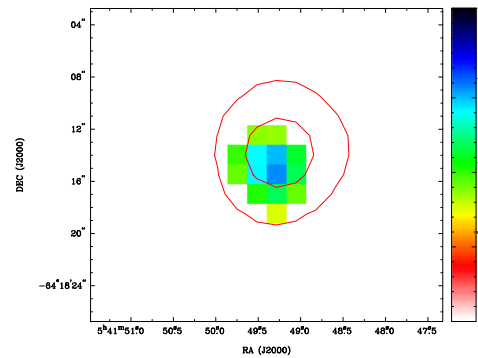
3.3 Luminosity of J054149.24–641813.7

Assuming a concordance cosmology with parameters provided by Planck Collaboration et al. (2016), the luminosity distance of NGC 2082 is $D_L = 17.5$ Mpc. The radio luminosity of J054149.24–641813.7 at 888 MHz is then $L_{888 \text{ MHz}} = 1.29 \times 10^{20} \text{ W Hz}^{-1}$ (with $\alpha = 0.02 \pm 0.09$). For comparison, the luminosity of the LMC's SN 1987A SNR (SNR 1987A) at its peak flux density ($S_{1000 \text{ MHz}} = 0.15 \text{ Jy}$; (Turtle et al. 1987)) is $L_{1000 \text{ MHz}} = 4.74 \times 10^{16} \text{ W Hz}^{-1}$ (with $\alpha = -0.74 \pm 0.02$ between 72 MHz and 8640 MHz (Callingham et al. 2016)) — 4 orders of magnitude smaller than J054149.24–641813.7. In addition to the very different radio spectral indexes of J054149.24–641813.7 and SNR 1987A, which indicate different emission origins, J054149.24–641813.7 is probably too bright to be an SNR originating from NGC 2082.

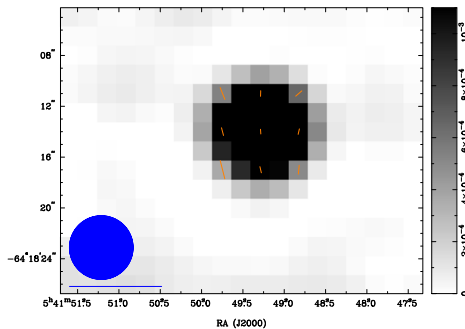
⁵<https://cartavis.org/>



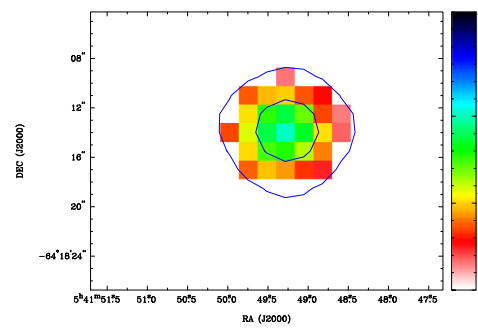
(a) Fractional polarisation map of J054149.24–641813.7 at 5500 MHz, where average $P_{5500\text{ MHz}} = 6 \pm 2\%$.



(b) Polarisation intensity map of J054149.24–641813.7 at 5500 MHz, with contours of 0.0003 and 0.002 Jy beam⁻¹



(c) Fractional polarisation map of J054149.24–641813.7 at 9000 MHz, where average $P_{9000\text{ MHz}} = 8 \pm 4\%$.



(d) Polarisation intensity map of J054149.24–641813.7 at 9000 MHz, with contours of 0.0002 and 0.002 Jy beam⁻¹

Fig. 3 Left: Fractional polarisation maps of the radio point source J054149.24–641813.7, where the circle on the lower-left corner represents a synthesised beam of 5×5 arcsec and the blue line below the circle represents 100 per cent polarisation. The bar on the right side

represents the grey-scale gradients for the ATCA image in Jy beam⁻¹. **Right:** Polarisation intensity maps of J054149.24–641813.7, where the bar on the right represents the colour-scale gradients for the ATCA image in Jy beam⁻¹

3.4 An FRB embedded in J054149.24–641813.7?

Fast radio bursts (FRBs) are extremely bright transient events of unknown origin (Lorimer et al. 2007). While FRBs can be associated with a variety of types of galaxies (e.g. Bhandari et al. 2020), two of the most active repeating FRBs 121102 (Chatterjee et al. 2017) and 190520B (Niu et al. 2021) are associated with compact persistent radio sources (PRSs). They also show large and variable DM and rotation measure (Michilli et al. 2018; Dai et al. 2022), indicating an extreme magneto-ionic local environment. The compact nature of J054149.24–641813.7 and its location at the outskirts of NGC 2082 are reminiscent of those of FRBs 121102 and 190520B.

FRB 121102’s PRS (QRS 121102) has a flat spectrum, with a spectral index of $\alpha = 0.07 \pm 0.03$ (Resmi et al. 2021), and its luminosity at 1600 MHz is $L_{1600\text{ MHz}} = 2.8 \times 10^{22} \text{ W Hz}^{-1}$ (Law et al. 2021) – two orders of magnitude greater than the luminosity of J054149.24–641813.7, $L_{1600\text{ MHz}} \approx L_{888\text{ MHz}} = 1.29 \times 10^{20} \text{ W Hz}^{-1}$. Chen et al. (2022) suggested that QRS121102 is too luminous to be an

SNR, consistent with our findings for J054149.24–641813.7 in Sect. 3.3.

190520B’s PRS (henceforth “QRS 190520B”) has a luminosity $L_{3000\text{ MHz}} = 3 \times 10^{22} \text{ W Hz}^{-1}$ and a spectral index of $\alpha = -0.41 \pm 0.04$ (Niu et al. 2021). Similarly, this is 2 orders of magnitude greater than the luminosity of J054149.24–641813.7, $L_{3000\text{ MHz}} \approx L_{888\text{ MHz}} = 1.29 \times 10^{20} \text{ W Hz}^{-1}$. Unlike QRS 121102 and J054149.24–641813.7, QRS 190520B’s spectral index is steep and negative – suggesting non-thermal emission as its origin.

Our Parkes observations (see Sect. 2.3) over 3 days detected no transient events. Despite this, considering both FRB 121102 and 190520B show sporadic outbursts (Rajwade et al. 2020; Dai et al. 2022), it is plausible that J054149.24–641813.7 could host a repeating FRB and we observed during a quiescent period.

3.5 J054149.24–641813.7 as a background object?

If intrinsic sources associated with J054149.24–641813.7 are implausible, the most likely remaining possibility is an

extragalactic background source, such as a quasar, radio galaxy or AGN. If so, we may expect to see some HI absorption; however, there is currently no high-resolution HI data for NGC 2082. The flat spectral index together with somewhat weak polarisation at 5500- and 9000-MHz images argue in favour of J054149.24–641813.7 background origin.

Our observations (Table 1) show that the flux density at 5000 MHz is ~ 4.0 mJy. From Wall (1994), we find that for observations at 5000 MHz there are ~ 15 sources/deg² at ≥ 4.0 mJy. The probability of finding a source of such brightness behind NGC 2082 is then,

$$P = A \times 15 \text{ sources/deg}^2,$$

where A is NGC 2082's area on the sky in deg². We calculate $P = 1.2\%$, given the radius of NGC 2082 is $r = 0.016$ deg (de Vaucouleurs et al. 1991).

4 Conclusions

Nearby spiral galaxy NGC 2082 was found to contain a bright, compact radio source, J054149.24–641813.7 (Fig. 1), which is most likely of background origin. The flux densities reveal J054149.24–641813.7 has a flat spectral index, indicating its source may be of thermal origin. We compare the luminosity of J054149.24–641813.7 to SNR 1987A, QRS 121102, and QRS 190520B, finding that J054149.24–641813.7 is likely too bright and flat to be a supernova, and is probably not bright enough to be a persistent radio source with an embedded FRB progenitor.

Acknowledgements The Australia Telescope Compact Array (ATCA) and Australian SKA Pathfinder (ASKAP) are part of the Australia Telescope National Facility that is managed by CSIRO. Operation of the ASKAP is funded by the Australian Government with support from the National Collaborative Research Infrastructure Strategy. The ASKAP uses the resources of the Pawsey Supercomputing Centre. Establishment of the ASKAP, the Murchison Radio-astronomy Observatory, and the Pawsey Supercomputing Centre are initiatives of the Australian Government, with support from the Government of Western Australia and the Science and Industry Endowment Fund. We acknowledge the Wajarri Yamatji people as the traditional owners of the Observatory site. SD is the recipient of an Australian Research Council Discovery Early Career Award (DE210101738) funded by the Australian Government. This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This research made use of APLpy, an open-source plotting package for Python (Robitaille and Bressert 2012). This research is based on observations made with the NASA/ESA Hubble Space Telescope, and obtained from the Hubble Legacy Archive, which is a collaboration between the Space Telescope Science Institute (STScI/NASA), the Space Telescope European Coordinating Facility (ST-ECF/ESA) and the Canadian Astronomy Data Centre (CADM/NRC/CSA). We thank the anonymous referee for a constructive report and useful comments.

Author Contribution Miroslav Filipovic and Shi Dai contributed to the original discovery, conception and design of this study. Parkes data collection and analysis were performed by Joel Balzan and Shi Dai. The first draft of this manuscript was written by Joel Balzan and all authors commented on previous versions of the manuscript. Rami Alsaberi observed and reduced ATCA data. All authors read and approved the final manuscript.

Funding Open Access funding enabled and organized by CAUL and its Member Institutions. No funding was acquired for this research.

Data Availability All data are publicly available:

- Parkes (project code PX075): <https://data.csiro.au/>
- ATCA CABB (project code C3275) and Pre-CABB (project code C466): <https://atoa.atnf.csiro.au/query.jsp>
- ASKAP (project code AS101): <https://data.csiro.au/>
- HST (proposal ID 9395): <https://hla.stsci.edu/hlview.html>

Declarations

Conflict of Interest The authors declare no competing interests.

Open Access This article is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons licence, and indicate if changes were made. The images or other third party material in this article are included in the article's Creative Commons licence, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons licence and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder. To view a copy of this licence, visit <http://creativecommons.org/licenses/by/4.0/>.

References

- Bates, S.D., Lorimer, D.R., Verbiest, J.P.W.: *Mon. Not. R. Astron. Soc.* **431**(2), 1352 (2013)
- Bhandari, S., Sadler, E.M., Prochaska, J.X., Simha, S., Ryder, S.D., Marnoch, L., Bannister, K.W., Macquart, J.-P., Flynn, C., Shannon, R.M., Tejos, N., Corro-Guerra, F., Day, C.K., Deller, A.T., Ekers, R., Lopez, S., Mahony, E.K., Nuñez, C., Phillips, C.: *Astrophys. J. Lett.* **895**(2), 37 (2020)
- Callingham, J.R., Gaensler, B.M., Zanardo, G., Staveley-Smith, L., Hancock, P.J., Hurley-Walker, N., Bell, M.E., Dwarakanath, K.S., Franzen, T.M.O., Hindson, L., Johnston-Hollitt, M., Kapińska, A., For, B.-Q., Lenc, E., McKinley, B., Morgan, J., Offringa, A.R., Procopio, P., Wayth, R.B., Wu, C., Zheng, Q.: *Mon. Not. R. Astron. Soc.* **462**(1), 290 (2016)
- Carollo, C.M., Stiavelli, M., Seigar, M., de Zeeuw, P.T., Dejonghe, H.: *Astron. J.* **123**(1), 159 (2002)
- Chatterjee, S., Law, C.J., Wharton, R.S., Burke-Spolaor, S., Hessels, J.W.T., Bower, G.C., Cordes, J.M., Tendulkar, S.P., Bassa, C.G., Demorest, P., Butler, B.J., Seymour, A., Scholz, P., Abruzzo, M.W., Bogdanov, S., Kaspi, V.M., Keimpema, A., Lazio, T.J.W., Marcote, B., McLaughlin, M.A., Paragi, Z., Ransom, S.M., Rupen, M., Spitler, L.G., van Langevelde, H.J.: *Nature* **541**(7635), 58 (2017)
- Chen, G., Ravi, V., Hallinan, G.W.: arXiv e-prints, 2201 (2022)
- Condon, J.J.: *Annu. Rev. Astron. Astrophys.* **30**, 575 (1992)

- Dai, S., Hobbs, G., Manchester, R.N., Kerr, M., Shannon, R.M., van Straten, W., Mata, A., Bailes, M., Bhat, N.D.R., Burke-Spolaor, S., Coles, W.A., Johnston, S., Keith, M.J., Levin, Y., Osłowski, S., Reardon, D., Ravi, V., Sarkissian, J.M., Tiburzi, C., Toomey, L., Wang, H.G., Wang, J.-B., Wen, L., Xu, R.X., Yan, W.M., Zhu, X.-J.: *Mon. Not. R. Astron. Soc.* **449**(3), 3223 (2015). <https://doi.org/10.1093/mnras/stv508.1503.01841>
- Dai, S., Feng, Y., Yang, Y.P., Zhang, Y.K., Li, D., Niu, C.H., Wang, P., Xue, M.Y., Zhang, B., Burke-Spolaor, S., Law, C.J., Lynch, R.S., Connor, L., Anna-Thomas, R., Zhang, L., Duan, R., Yao, J.M., Tsai, C.W., Zhu, W.W., Cruces, M., Hobbs, G., Miao, C.C., Niu, J.R., Filipović, M.D., Zhu, S.Q.: *arXiv e-prints*, 2203 (2022)
- de Vaucouleurs, G., de Vaucouleurs, A., Corwin, J., Herold, G., Buta, R.J., Paturel, G., Fouque, P.: *Third Reference Catalogue of Bright Galaxies*, Springer, New York (1991)
- Evans, R., Phillips, M.M.: *IAU Circ.* **5625**, 2 (1992)
- Filipović, M.D., Bojičić, I.S., Grieve, K.R., Norris, R.P., Tohill, N.F.H., Shobhana, D., Rudnick, L., Prandoni, I., Andernach, H., Hurley-Walker, N., Alsaberi, R.Z.E., Anderson, C.S., Collier, J.D., Crawford, E.J., For, B.-Q., Galvin, T.J., Haberl, F., Hopkins, A.M., Ingallinera, A., Kavanagh, P.J., Koribalski, B.S., Kothés, R., Leahy, D., Leverenz, H., Maggi, P., Maitra, C., Marvil, J., Pannuti, T.G., Park, L.A.F., Payne, J.L., Pennock, C.M., Riggi, S., Rowell, G., Sano, H., Sasaki, M., Staveley-Smith, L., Triggilio, C., Umana, G., Urošević, D., van Loon, J.T., Vardoulaki, E.: *Mon. Not. R. Astron. Soc.* **507**(2), 2885 (2021)
- Filipović, M.D., Payne, J.L., Alsaberi, R.Z.E., Norris, R.P., Macgregor, P.J., Rudnick, L., Koribalski, B.S., Leahy, D., Ducci, L., Kothés, R., Andernach, H., Barnes, L., Bojičić, I.S., Bozzetto, L.M., Brose, R., Collier, J.D., Crawford, E.J., Crocker, R.M., Dai, S., Galvin, T.J., Haberl, F., Heber, U., Hill, T., Hopkins, A.M., Hurley-Walker, N., Ingallinera, A., Jarrett, T., Kavanagh, P.J., Lenc, E., Luken, K.J., Mackey, D., Manojlović, P., Maggi, P., Maitra, C., Pennock, C.M., Points, S., Riggi, S., Rowell, G., Safi-Harb, S., Sano, H., Sasaki, M., Shabala, S., Stevens, J., van Loon, J.T., Tohill, N.F.H., Umana, G., Urošević, D., Velović, V., Vernstrom, T., West, J.L., Wan, Z.: *Mon. Not. R. Astron. Soc.* **512**(1), 265 (2022). <https://doi.org/10.1093/mnras/stac210.2201.10026>
- Filipović, M.D., Tohill, N.F.H. (eds.): *Multimessenger Astronomy in Practice*. 2514-3433 IOP Publishing, Bristol, UK (2021a). <https://doi.org/10.1088/2514-3433/ac2256>
- Filipović, M.D., Tohill, N.F.H.: *Principles of Multimessenger Astronomy*, pp. 2514–3433. IOP Publishing, Bristol, UK (2021b). <https://doi.org/10.1088/2514-3433/ac087e>
- Gioia, I.M., Gregorini, L., Klein, U.: *Astron. Astrophys.* **116**(1), 164 (1982)
- Gooch, R.: In: Shaw, R.A., Payne, H.E., Hayes, J.J.E. (eds.) *Astronomical Data Analysis Software and Systems IV*. Astronomical Society of the Pacific Conference Series, vol. 77, p. 144 (1995)
- Hobbs, G., Manchester, R.N., Dunning, A., Jameson, A., Roberts, P., George, D., Green, J.A., Tuthill, J., Toomey, L., Kaczmarek, J.F., et al.: *Proc. Astron. Soc. Aust.* **37** (2020)
- Hurley-Walker, N., Gaensler, B.M., Leahy, D.A., Filipović, M.D., Hancock, P.J., Franzen, T.M.O., Offringa, A.R., Callingham, J.R., Hindson, L., Wu, C., Bell, M.E., For, B.-Q., Johnston-Hollitt, M., Kapińska, A.D., Morgan, J., Murphy, T., McKinley, B., Procopio, P., Staveley-Smith, L., Wayth, R.B., Zheng, Q.: *Proc. Astron. Soc. Aust.* **36**, 048 (2019a)
- Hurley-Walker, N., Filipović, M.D., Gaensler, B.M., Leahy, D.A., Hancock, P.J., Franzen, T.M.O., Offringa, A.R., Callingham, J.R., Hindson, L., Wu, C., et al.: *Proc. Astron. Soc. Aust.* **36**, 045 (2019b)
- Lauberts, A., Valentijn, E.A.: *The Surface Photometry Catalogue of the ESO-Uppsala Galaxies*. European Southern Observatory, Garching (1989)
- Law, C.J., Connor, L., Aggarwal, K.: *arXiv e-prints*, 2110 (2021)
- Lorimer, D.R., Bailes, M., McLaughlin, M.A., Narkevic, D.J., Crawford, F.: *Science* **318**(5851), 777 (2007)
- Michilli, D., Seymour, A., Hessels, J.W.T., Spitler, L.G., Gajjar, V., Archibald, A.M., Bower, G.C., Chatterjee, S., Cordes, J.M., Gourdji, K., Heald, G.H., Kaspi, V.M., Law, C.J., Sobey, C., Adams, E.A.K., Bassa, C.G., Bogdanov, S., Brinkman, C., Demorest, P., Fernandez, F., Hellbourg, G., Lazio, T.J.W., Lynch, R.S., Maddox, N., Marcote, B., McLaughlin, M.A., Paragi, Z., Ransom, S.M., Scholz, P., Siemion, A.P.V., Tendulkar, S.P., van Rooy, P., Wharton, R.S., Whitlow, D.: *Nature* **553**(7687), 182 (2018)
- Niu, C.-H., Aggarwal, K., Li, D., Zhang, X., Chatterjee, S., Tsai, C.-W., Yu, W., Law, C.J., Burke-Spolaor, S., Cordes, J.M., Zhang, Y.-K., Ocker, S., Yao, J.-M., Wang, P., Feng, Y., Niino, Y., Bochenek, C., Cruces, M., Connor, L., Jiang, J.-A., Dai, S., Luo, R., Li, G.-D., Miao, C.-C., Niu, J.-R., Anna-Thomas, R., Sydnor, J., Stern, D., Wang, W.-Y., Yuan, M., Yue, Y.-L., Zhou, D.-J., Yan, Z., Zhu, W.-W., Zhang, B.: *arXiv e-prints*, 2110 (2021)
- Olivares E., F., Hamuy, M., Pignata, G., Maza, J., Bersten, M., Phillips, M.M., Suntzeff, N.B., Filippenko, A.V., Morrel, N.I., Kirshner, R.P., Matheson, T.: *Astrophys. J.* **715**(2), 833 (2010)
- Pennock, C.M., van Loon, J.T., Filipović, M.D., Andernach, H., Haberl, F., Kothés, R., Lenc, E., Rudnick, L., White, S.V., Agliozzo, C., Antón, S., Bojičić, I., Bomans, D.J., Collier, J.D., Crawford, E.J., Hopkins, A.M., Jeganathan, K., Kavanagh, P.J., Koribalski, B.S., Leahy, D., Maggi, P., Maitra, C., Marvil, J., Michałowski, M.J., Norris, R.P., Oliveira, J.M., Payne, J.L., Sano, H., Sasaki, M., Staveley-Smith, L., Vardoulaki, E.: *Mon. Not. R. Astron. Soc.* **506**(3), 3540 (2021)
- Planck Collaboration, Ade, P.A.R., Aghanim, N., Arnaud, M., Ashdown, M., Aumont, J., Baccigalupi, C., Banday, A.J., Barreiro, R.B., Bartlett, J.G., Bartolo, N., Battaner, E., Battye, R., Benabed, K., Benoît, A., Benoit-Lévy, A., Bernard, J.-P., Bersanelli, M., Bielewicz, P., Bock, J.J., Bonaldi, A., Bonavera, L., Bond, J.R., Borrill, J., Bouchet, F.R., Boulanger, F., Bucher, M., Burigana, C., Butler, R.C., Calabrese, E., Cardoso, J.-F., Catalano, A., Challinor, A., Chhaballu, A., Chary, R.-R., Chiang, H.C., Chluba, J., Christensen, P.R., Church, S., Clements, D.L., Colombi, S., Colombo, L.P.L., Combet, C., Coulais, A., Crill, B.P., Curto, A., Cuttaia, F., Danese, L., Davies, R.D., Davis, R.J., de Bernardis, P., de Rosa, A., de Zotti, G., Delabrouille, J., Désert, F.-X., Di Valentino, E., Dickinson, C., Diego, J.M., Dolag, K., Dole, H., Donzelli, S., Doré, O., Douspis, M., Ducout, A., Dunkley, J., Dupac, X., Efstathiou, G., Elsner, F., Enßlin, T.A., Eriksen, H.K., Farhang, M., Fergusson, J., Finelli, F., Forni, O., Frailis, M., Fraisse, A.A., Franceschi, E., Frejsel, A., Galeotta, S., Galli, S., Ganga, K., Gauthier, C., Gerbino, M., Ghosh, T., Giard, M., Giraud-Héraud, Y., Giusarma, E., Gjerløw, E., González-Nuevo, J., Górski, K.M., Gratton, S., Gregorio, A., Gruppuso, A., Gudmundsson, J.E., Hamann, J., Hansen, F.K., Hanson, D., Harrison, D.L., Helou, G., Henrot-Versillé, S., Hernández-Monteagudo, C., Herranz, D., Hildebrandt, S.R., Hivon, E., Hobson, M., Holmes, W.A., Hornstrup, A., Hovest, W., Huang, Z., Huffenberger, K.M., Hurier, G., Jaffe, A.H., Jaffe, T.R., Jones, W.C., Juvela, M., Keihänen, E., Keskitalo, R., Kisner, T.S., Kneissl, R., Knoch, J., Knox, L., Kunz, M., Kurki-Suonio, H., Lagache, G., Lähteenmäki, A., Lamarre, J.-M., Lasenby, A., Lattanzi, M., Lawrence, C.R., Leahy, J.P., Leonardi, R., Lesgourgues, J., Levrier, F., Lewis, A., Liguori, M., Lilje, P.B., Linden-Vørnle, M., López-Cañiego, M., Lubin, P.M., Macías-Pérez, J.F., Maggio, G., Maino, D., Mandolesi, N., Mangilli, A., Marchini, A., Maris, M., Martin, P.G., Martinelli, M., Martí nez-González, E., Masi, S., Matarrese, S., McGehee, P., Meinhold, P.R., Melchiorri, A., Melin, J.-B., Mendes, L., Mennella, A., Migliaccio, M., Millea, M., Mitra, S., Miville-Deschênes, M.-A., Moneti, A., Montier, L., Morgante, G., Mortlock, D., Moss, A., Munshi, D., Murphy, J.A., Naselsky, P., Nati, F., Natoli, P., Netterfield, C.B., Nørgaard-Nielsen,

- H.U., Noviello, F., Novikov, D., Novikov, I., Oxborrow, C.A., Paci, F., Pagano, L., Pajot, F., Paladini, R., Paoletti, D., Partridge, B., Pasian, F., Patanchon, G., Pearson, T.J., Perdereau, O., Perotto, L., Perrotta, F., Pettorino, V., Piacentini, F., Piat, M., Pierpaoli, E., Pietrobon, D., Plaszczynski, S., Pointecouteau, E., Polenta, G., Popa, L., Pratt, G.W., Prézeau, G., Prunet, S., Puget, J.-L., Rachen, J.P., Reach, W.T., Rebolo, R., Reinecke, M., Remazeilles, M., Renault, C., Renzi, A., Ristorcelli, I., Rocha, G., Rosset, C., Rossetti, M., Roudier, G., Rouillé d'Orfeuille, B., Rowan-Robinson, M., Rubiño-Martín, J.A., Rusholme, B., Said, N., Salvatelli, V., Salvati, L., Sandri, M., Santos, D., Savelainen, M., Savini, G., Scott, D., Seiffert, M.D., Serra, P., Shellard, E.P.S., Spencer, L.D., Spinelli, M., Stolyarov, V., Stompor, R., Sudiwala, R., Sunyaev, R., Sutton, D., Suur-Uski, A.-S., Sygnet, J.-F., Tauber, J.A., Terenzi, L., Toffolatti, L., Tomasi, M., Tristram, M., Trombetti, T., Tucci, M., Tuovinen, J., Türler, M., Umana, G., Valenziano, L., Valiviita, J., Van Tent, F., Vielva, P., Villa, F., Wade, L.A., Wandelt, B.D., Wehus, I.K., White, M., White, S.D.M., Wilkinson, A., Yvon, D., Zacchei, A., Zonca, A.: *Astron. Astrophys.* **594**, 13 (2016)
- Rajwade, K.M., Mickaliger, M.B., Stappers, B.W., Morello, V., Agarwal, D., Bassa, C.G., Breton, R.P., Caleb, M., Karastergiou, A., Keane, E.F., Lorimer, D.R.: *Mon. Not. R. Astron. Soc.* **495**(4), 3551 (2020)
- Ransom, S.M.: New search techniques for binary pulsars. PhD thesis, Harvard University (2001)
- Resmi, L., Vink, J., Ishwara-Chandra, C.H.: *Astron. Astrophys.* **655**, 102 (2021)
- Robitaille, T., Bressert, E.: *APLpy: Astronomical Plotting Library in Python* (2012)
- Sault, R.J., Teuben, P.J., Wright, M.C.H.: In: Shaw, R.A., Payne, H.E., Hayes, J.J.E. (eds.) *Astronomical Data Analysis Software and Systems IV. Astronomical Society of the Pacific Conference Series*, vol. 77, p. 433 (1995)
- Turtle, A.J., Campbell-Wilson, D., Bunton, J.D., Jauncey, D.L., Kesteven, M.J., Manchester, R.N., Norris, R.P., Storey, M.C., Reynolds, J.E.: *Nature* **327**(6117), 38 (1987)
- Urošević, D.: *Astrophys. Space Sci.* **354**(2), 541 (2014)
- Wall, J.V.: *Aust. J. Phys.* **47**, 625 (1994). <https://doi.org/10.1071/PH940625>
- Publisher's Note** Springer Nature remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.