Discovery of a new extragalactic circular radio source with ASKAP: ORC J0102–2450

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ABSTRACT
We present the discovery of another Odd Radio Circle (ORC) with the Australian Square Kilometre Array Pathfinder (ASKAP) at 944 MHz. The observed radio ring, ORC J0102–2450, has a diameter of 70 arcsec or 300 kpc, if associated with the central elliptical galaxy DES J010224.33–245039.5 (z ∼ 0.27). Considering the overall radio morphology (circular ring and core) and lack of ring emission at non-radio wavelengths, we investigate if ORC J0102–2450 could be the relic lobe of a giant radio galaxy seen end-on or the result of a giant blast wave. We also explore possible interaction scenarios, for example, with the companion galaxy, DES J010226.15–245104.9, located in or projected onto the south-eastern part of the ring. We encourage the search for further ORCs in radio surveys to study their properties and origin.

Key words: radio continuum: galaxies, ISM – instrumentation: radio interferometers

1 INTRODUCTION
Odd radio circles (ORCs), first discovered by Norris et al. (2021a) in ASKAP radio continuum data from the ‘Evolutionary Map of the Universe’ (EMU) Pilot Survey (800 – 1088 MHz; rms ∼ 30 μJy beam−1), resemble rings or edge-brightened disks of radio emission that, so far, remain undetected at non-radio wavelengths. In their paper, Norris et al. present four ORCs (each ∼60 arcsec in diameter), three of which were detected with ASKAP, including a pair of ORCs. The fourth ORC, which is notable for its central radio source, was discovered in 325 MHz radio data from the Giant Meterwave Radio Telescope (GMRT). Most notably, the two single ORCs each have an elliptical galaxy in their geometrical ring centre.

Odd Radio Circles – at first glance – look like supernova remnants (SNRs), so could they be formed by a giant blast wave from a transient event (e.g., a merging binary super-massive black hole (SMBH), a hyper-nova, or a γ-ray burst) in the central elliptical galaxy many millions of years ago? In Norris et al. (2021a) a wide range of possible formation scenarios are discussed, which are evaluated and expanded with each new ORC discovery.

In this paper we focus on ORC J0102–2450, newly discovered during the search for ORCs and other extended radio sources in a deep ∼40 deg2 ASKAP field centred near the starburst galaxy NGC 253. A summary of the ASKAP multi-epoch observations is given in Section 2, followed by our analysis of the ORC J0102–2450 properties in Section 3. Possible formation scenarios are discussed in Section 4, and our conclusions are given in Section 5.

2 ASKAP OBSERVATIONS AND DATA PROCESSING
ASKAP is a new radio interferometer consisting of 36 × 12-m antennas, each equipped with a wide-field Phased Array Feed (PAF), baselines out to 6.4 km, operating at frequencies from 700 MHz to 1.8 GHz (Johnston et al. 2008). The currently available bandwidth of 288 MHz is divided into 288 MHz coarse channels; for a comprehensive system overview see Hotan et al. (2021). We obtained nine fully calibrated ASKAP radio continuum images (∼10h integration time each) from the CSIRO ASKAP Science Data Archive (CASDA)1. The field centres are close to the nearby starburst galaxy NGC 253 (HIPASS J0047–25; PKS J0047–2517), which has a total integrated flux density of 6.2 Jy at 1.4 GHz and 8.1 Jy at 960 MHz (Kühr et al. 1981). The brightness and large extent of the NGC 253 star-forming disc causes minor artefacts over most of the field at a flux level of ≤1%. The nine ASKAP observations were conducted between Aug 2019 and Dec 2020 with the band centred at 943.5 MHz. ASKAP PAFs were used to form 36 beams arranged in a 6 × 6 closepack 36 footprint (Hotan et al. 2021), each delivering a

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ORC J0102–2450. — ASKAP radio continuum contours overlaid onto an optical RGB colour image created from the Dark Energy Survey (DES) zrg-bands. The ASKAP radio contour levels are 0.045 (dark red), 0.065, 0.09, 0.12, 0.17, 0.22, 0.27, 0.4, 0.6 and 0.8 mJy beam$^{-1}$; the resolution is 13$''$ and the rms is ~15$\mu$Jy beam$^{-1}$. DES image cutouts of the three radio-detected galaxies and their average photometric redshifts are shown on the right side (top: background galaxy, middle: central galaxy, bottom: south-eastern galaxy).

We combined eight of the nine ASKAP radio continuum images (leaving out the last, rather short observation) after convolving each to a common 13$''$ resolution, achieving an rms sensitivity of ~15$\mu$Jy beam$^{-1}$ near ORC J0102–2450. We then measured the ring diameter and width, finding a diameter of ~300 kpc and an average ring width of ~25 arcsec from the ridge line to the 50% intensity.

ORC J0102–2450 has a possible unresolved low-frequency counterpart, GLEAMSGP J010224–245024 (Franzen et al. 2021), but data at higher resolution and sensitivity are needed to confirm this. Using the fitted GLEAMSGP 200 MHz (resolution $\approx$2$'$) and the ASKAP 944 MHz flux densities for the same area (17±1 mJy and 3.9 mJy, respectively), we estimate a black hole mass of ~7.5 $\times$ 10$^8$ M$_\odot$ following Graham (2007). The total integrated flux density of ORC J0102–2450 as measured in our ASKAP 944 MHz data is ~3.9 mJy. It is clearly detected in Stokes I in each of the nine epochs; no polarization has been detected.

A prominent radio peak within the south-eastern (SE) part of the ring (~0.25 mJy beam$^{-1}$) corresponds to the galaxy WISEA J010226.15–245104.9 (DES J010226.15–245104.9). It has a similar redshift to the central galaxy (see Table 1), suggesting they form a physical galaxy pair and are likely interacting. The WISE colours (see Fig. 2) suggest it is a star-forming galaxy or LIRG (Jarrett et al. 2017). A polar projection of the ORC is shown in Fig. 3. In addition to the central radio core/jet, we detect diffuse radio emission inside and outside of the ring, extending out to a diameter of ~120 arcsec (500 kpc). Although this emission is faint, it may account for a significant fraction of the total ORC flux.

No optical or infrared counterparts to the radio ring have been detected, apart from a luminous infrared galaxy (LIRG) in the south-eastern section, which is discussed below. The weak central radio source is located at $\alpha, \delta$(J2000) = 01$^h$02$^m$24.5$^s$, –24°50'38'' (~0.1 mJy), coincident with a bright elliptical galaxy (see Table 1). The classification of this galaxy as an elliptical, based on the WISE colour-colour diagram (Jarrett et al. 2017), is likely. From the 2MASS K$_s$-band luminosity of the central galaxy in ORC J0102–2450, we estimate a black hole mass of ~7.5 $\times$ 10$^8$ M$_\odot$ following Graham (2007). The total integrated flux density of ORC J0102–2450 as measured in our ASKAP 944 MHz data is ~3.9 mJy. It is clearly detected in Stokes I in each of the nine epochs; no polarization has been detected.

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In the following we focus on possible ORC central radio sources, in positional agreement with their proposed cm observationsof ORC1 (Norris et al., priv. comm.), all three have summarised in Table 2. Taking into account recent MeerKAT 20-redshifts, spectral indices and central elliptical host galaxies, as radio source and is not further considered here. Different with neither having an associated host galaxy nor a central very small, further candidate ORCs with similar features are under

### 4 DISCUSSION

Here we discuss possible explanations for the origin of ORCs. Of the four ORCs discussed by Norris et al. (2021a), two — ORCs 1 & 4 — have clear similarities to our discovery. See Table 2 for a brief summary of their properties. Most notably, each of the three ORCs has an elliptical galaxy in their respective ring centre, which is unlikely a coincidence. The probability of finding a radio source randomly coincident with the central 10" of the ring is only \(5 \times 10^{-7}\), based on the EMU source density of 814 deg\(^{-2}\) for a 5\(\sigma\) threshold (Norris et al., in prep.). While a class of three objects is very small, further candidate ORCs with similar features are under investigation. The double ORC feature (ORCs 2 & 3) is distinctly different with neither having an associated host galaxy nor a central radio source and is not further considered here.

The three ORCs have similar sizes, morphologies, brightness, redshifts, spectral indices and central elliptical host galaxies, as summarised in Table 2. Taking into account recent MeerKAT 20-cm observations of ORC 1 (Norris et al., priv. comm.), all three have central radio sources, in positional agreement with their proposed elliptical host galaxies. In the following we focus on possible ORC formation scenarios where the observed radio rings are primarily associated with the central elliptical galaxies. Could ORCs be the projected view of a giant radio galaxy lobe seen end-on? Or are we seeing a new class of radio source? The similarity in morphology to Galactic SNRs suggests an energetic transient event may be responsible for a spherical shock wave of radio emission. Or could ORCs be the result of complex interactions, where the bent radio tails of one or two galaxies form a ring-structure?

#### 4.1 Giant radio lobes seen end-on

One possible explanation is that ORCs are relic radio galaxy lobes seen end-on, possibly in a rare transition state where the central jet has switched off but the shells of fading lobes are still expanding into the surrounding intergalactic medium (IGM). The circular shapes of ORCs and their central (host) galaxies require alignment of the radio shells with the observer’s line-of-sight, suggesting they are unperturbed by the surrounding IGM. The ORC diameters of 300 – 500 kpc suggest that we are dealing with giant radio galaxies (GRGs), the elliptical hosts galaxies of which lie in the respective ring centres. Given the ORC spectral indices (see Table 2), higher resolution observations, especially at lower frequencies, are expected to detect many more ORCs. Radio galaxies seen oriented in such a way must exist, but may not necessarily look like ORCs. An example of a relic giant radio galaxy with nearly straight lobes that fit this scenario is presented by Tamhane et al. (2015). Viewed end-on, it may resemble an ORC.

This scenario is supported by 2D hydrodynamical simulations (e.g., Brüggen & Kaiser 2001) who investigate the expansion and shape of radio lobes after the SMBH-driven jet has turned off, finding large bubbles and toroidal shapes that may resemble ORCs when seen end-on. These appear to be short-lived unless re-energised (e.g., Subrahmanyan et al. 2008; Murgia et al. 2011; Tamhane et al. 2015), contributing to the rarity of ORCs. Noiting et al. (2019) in their simulations find “vortex rings” — which resemble ORCs — resulting from a shock by a head-on collision of a radio galaxy lobe with a stationary plane of hot intracluster gas. Detailed 3D simulations of the remnant radio galaxy scenarios are currently underway, and will be reported in a subsequent publication.

#### 4.2 Radio remnant of a giant blast wave

Could ORCs be the result of a giant blast wave in the central galaxy, producing a spherical shell of radio emission? Such shells would appear as edge-brightened discs, similar to supernova remnants or planetary nebulae. The radio emission is presumably synchrotron emission from electrons accelerated by a shock (e.g., Downes et al. 2002; Cao & Wang 2012; Ricci et al. 2021). The edge-brightened emission is caused by the long path length through the limbs of the region, while the diffuse emission within the ring is caused by the front and back hemispheres of the shell. The thickness of the shell would determine the ratio of the ring emission brightness to the diffuse emission brightness. One way to produce such a spherical shock would be as the result of a binary SMBH merger in the central galaxy (e.g., Bode et al. 2012). In that case, we would expect to observe a largely tangential magnetic field in the ring, orthogonal to the velocity of the shock, similar to that of supernova remnants or cluster relics. Assuming the blastwave evolution is dominated by the Sedov-Taylor phase, for a fiducial ICM density of \(10^{-3}\) cm\(^{-3}\) and a sound speed of 1000 km s\(^{-1}\) we estimate a blastwave age of \(t = 57/M\) Myr and energy \(E = (6 \times 10^{53}/M^2)\) Joules, where \(M\) is the mass of the central galaxy. ~5 mJy, respectively, i.e. the ORC and neighboring ~1 mJy point source, we derive a 200–944 MHz spectral index of \(\alpha = -0.8 \pm 0.2\), assuming \(S \propto \nu^\alpha\) where \(S\) is the flux density at frequency \(\nu\).
Figure 2. ASKAP radio continuum contours of ORC J0102–2450 overlaid onto a WISE RGB colour image (red: 12\(\mu\)m (W3), green: 4.6\(\mu\)m (W2), and 3.4\(\mu\)m (W1) – at 7 arcsec resolution; left), a DES r-band grey-scale image (middle), and an ASKAP/DES combined RGB colour image, where the ASKAP image is shown in a combination of blue and red, while the DES r-band image is coloured green (right). The ASKAP radio contour levels are \(-0.045, 0.045 \times 3\sigma, 0.065, 0.09, 0.17, 0.22, 0.27, 0.4, 0.6\) and \(0.8\) mJy beam\(^{-1}\); the resolution is 13\(\arcsec\) and the rms is \(15\mu\)Jy beam\(^{-1}\).

Table 2. Properties of three ORCs with central galaxies.

| source name            | discovery telescope | central host galaxy | galaxy redshift | ring diameter [arcsec] | ring diameter [kpc] | spectral index | Ref.                |
|------------------------|---------------------|---------------------|-----------------|------------------------|---------------------|-----------------|---------------------|
| ORC J2103–6200 (ORC 1) | ASKAP               | WISE J210258.15–620014.4 | 0.55            | 80                     | 510                 | \(-1.17 \pm 0.04\) | Norris et al. 2021a |
| ORC J1555+2726 (ORC 4) | GMRT                | WISE J155524.65+272633.7 | 0.39            | 70                     | 370                 | \(-0.92 \pm 0.18\) | Norris et al. 2021a |
| ORC J0102–2450 (ORC 5) | ASKAP               | DES J010224.33–245039.5 | 0.27            | 70                     | 300                 | \(-0.8 \pm 0.2\)  | this paper          |

is the current Mach number of the expanding shell. For transonic Mach numbers, this energy corresponds to a mass deficit of several million \(M_\odot\), broadly consistent with a supermassive black hole merger scenario.

4.3 Interaction scenarios

Could the galaxy DES J010226.15–245104.9 (\(z = 0.26\)), located in the radio ring \(-150\) kpc southeast of the ORC centre (SE galaxy in Table 2), possibly be the host of a radio galaxy with two narrow tails curving to form an incomplete ring? This scenario arises for ORC J0102–2450 because of its C-shaped structure, where the eastern, somewhat brighter side of the radio ring could be interpreted as a radio tail emerging northwards from the SE galaxy. The galaxy’s radio flux density is \(0.25\) mJy. In this scenario, each of the narrow, curved radio tails would span \(-300\) kpc. This may also be applicable to ORC 1 (Norris et al. 2021a) with DES J210257.79–620045.9 (\(z = 0.077\)) in the southern part of the ring being the possible host galaxy. Narrow- and wide-angle tail radio galaxies are generally found in merging clusters where it is proposed that their motion through the intracluster medium (ICM) shapes their lobes (e.g., Smolčić et al. 2007, and references therein). The ORCs do not appear to reside in clusters, and this scenario fails to explain their central galaxies.

Could interactions between the two galaxies and their radio lobes be responsible for the observed ORC shape? For spiral galaxies, interactions typically result in tidal tails, bridges and filaments, which can have a wide range of shapes and sizes (for a review see Koribalski 2019). A beautiful example of gravitational and ram pressure interaction between two double-lobe radio galaxies exist in the Abell 3785 cluster. The radio galaxy pair P KS 2130–538 (Jones & McAdam 1992) with host galaxies PGC 66975/6 (both at \(z = 0.077\)), separated by \(-350\) kpc, is also detected in the EMU Pilot Survey (Norris et al., in prep.). It seems unlikely that two interacting radio galaxies would be able to form the observed radio ring. Simulations of helical jets have succeeded in creating radio rings, like the doughnut shaped counter-minilobe of NGC 6109 which lies opposite a long (helical) radio tail (Rawes et al. 2018). A helical lobe structure may contribute to the brightness variations of an end-on lobe view.

5 CONCLUSIONS

Our discovery of ORC J0102–2450 with ASKAP makes it the third odd radio circle with an elliptical galaxy at its geometrical centre. This is unlikely a coincidence and brings us a step closer to determining the ORC formation mechanisms. We discussed three scenarios, two of which have the central galaxy as its basis. These are (1) a relic lobe of a giant radio galaxy seen end-on or (2) a giant blast wave, possibly from a binary SMBH merger, resulting in a radio ring of \(300 \sim 500\) kpc diameter. The third scenario considers radio galaxy and IGM interactions, involving the companion galaxy, that may be able to create the observed ring structure.

The discovery of further ORCs in the rapidly growing amount of wide-field radio continuum data from ASKAP and other telescopes will show if the above scenarios have any merit, contributing to exciting times in astronomy. Low-frequency LOFAR surveys at high-resolution (6\(\arcsec\)) will be of particular interest (see Shimwell et al. 2019), given the steep spectral index of known ORCs. Deep
X-ray observations may also detect these energetic events as shown in the case of a giant relic radio galaxy by Tamhane et al. (2015).

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DATA AVAILABILITY

The ASKAP data used in this article are available through the CSIRO ASKAP Science Data Archive (CASDA) under https://doi.org/10.25919/5e5d13e6bda0c. Additional data processing and analysis was conducted using the miriad software\textsuperscript{2} and the Karma visualisation\textsuperscript{3} packages. DES and WISE images were obtained through the Astro Data Lab\textsuperscript{4} and SkyView\textsuperscript{5} servers, respectively.

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