Odd radio circles (ORCs) are a newly discovered class of extended faint radio sources of unknown origin. We report the first detection of diffuse X-ray gas at the location of a low-redshift ORC (z = 0.046) known as Cloverleaf ORC. This observation was performed with the *XMM-Newton* X-ray telescope. The physical extent of the diffuse X-ray emission corresponds to a region of approximately 230 kpc by 160 kpc, lying perpendicular to the radio emission detected by ASKAP. The X-ray spectrum shows characteristics of thermal multiphase gas with temperatures of 1.10 ± 0.08 keV and 0.22 ± 0.01 keV and a central density of (4.9 ± 0.6) × 10^-4 cm^-3, indicating that the Cloverleaf ORC resides in a low-mass galaxy group. Using X-ray observations, with hydrostatic equilibrium and isothermal assumptions, we measure the galaxy group to have a gas mass and a total mass of (7 ± 1) × 10^11 M_☉ and 3.4 ± 0.5 × 10^14 M_☉ within the overdensity radius R_500. The presence of a high-velocity subgroup identified in optical data, the orientation of the brightest cluster galaxy, the disturbed morphologies of galaxies toward the east of the Cloverleaf ORC, and the irregular morphology of the X-ray emission suggest that this system is undergoing a galaxy group merger. The radio power of the ORC could be explained by the shock reacceleration of fossil cosmic rays generated by a previous episode of black hole activity in the central active galactic nucleus.

**Key words.** galaxies: evolution – galaxies: groups: general – radio continuum: galaxies – X-rays: galaxies

**1. Introduction**

Recent radio surveys, including the Australian SKA Pathfinder (ASKAP), revealed a novel category of faint radio sources known as odd radio circles (ORCs), which were later confirmed with the Giant Metrewave Radio Telescope (GMRT) and MeerKAT (Norris et al. 2021; Koribalski et al. 2021, 2023; Lochner et al. 2023). Only eight ORCs are associated with an optical counterpart, elliptical galaxies with reported stellar masses of approximately ~10^{11} M_☉, also known as cosmological or extragalactic ORCs. The redshifts of the galaxies associated with the known ORCs range between 0.05 and 0.6, with a typical ORC size of 300 kpc to 500 kpc. Many of these sources have large ring-like emission, bright and clumpy at the edges, with several irregular emission peaks in their centers. The reported radio powers are several times 10^{23} W Hz^-1 and have radio brightness of 2–9 mJy at GHz frequencies.

Various physical explanations of the nature of the extragalactic ORCs are proposed. These include the forward termination shock resulting from past starburst events (Norris et al. 2021, 2022), binary supermassive black hole mergers (Koribalski et al. 2021; Norris et al. 2022), supernova remnants within the Local Group (Filipović et al. 2022; Omar 2022; Sarbadhicary et al. 2023), tidal disruptions of stars by intermediate-mass or supermassive black holes (Omar 2022), synchrotron emission from virial shocks around massive galaxies (Yamasaki et al. 2024) and synchrotron emission from the historical activity of galactic outflows (Coil et al. 2024), and end-on active galactic nucleus (AGN) jet-inflated bubbles (Lin & Yang 2024).

Recently, Dolag et al. (2023) postulated that the internal shocks from forming the group-size halos might explain the detection frequency and morphology of the ORC populations by employing nonradiative high-resolution simulations of a Milky Way-mass galactic halo. The halos with the dark matter halo virial mass of 10^{12}–10^{13} M_☉ with stellar masses of several times 10^{11} M_☉, with internal shock Mach number 2.1–2.4 may explain these observed features. However, a direct shock acceleration mechanism of the cosmic-ray electrons fails to reproduce the observed luminosities of the radio emission.

The Cloverleaf ORC, discovered by the Australian SKA Pathfinder (ASKAP), is one of the lowest redshift ORCs known to date (Dolag et al. 2023; Koribalski et al., in prep.). The optical counterpart of the ORC is the elliptical galaxy GAMA J113727.46–005047.6 at (RA: 174°46′ Dec: −8.8467°), hereafter brightest cluster galaxy 1 (BCG1), with a stellar mass of 1.4 ± 0.3 × 10^{11} M_☉ with a spectroscopic redshift of 0.046399 ± 1.2 × 10^{-5} (Driver et al. 2022). Previously, the Cloverleaf system was cataloged as a galaxy group under the name MZ 07128 in the 2dF survey (2dFGGC) galaxy group catalog in the Sloan Digital Sky Survey (SDSS) or the 6dFGS galaxy cluster catalog. The galaxy group merger origin of the Cloverleaf odd radio circle system is explored in this Letter to the Editor.
Fig. 1. Multi-wavelength image of the Cloverleaf odd radio circle system. Left: DESI Legacy Survey DR10 optical (white to yellow), XMM-Newton X-ray (blue), and ASKAP radio continuum (red) composite image of the Cloverleaf ORC. Middle: zoomed-in views of three morphologically disturbed galaxies (A, B, C) to the east and morphologically undisturbed galaxy (D) to the west. The BCG1, located at the X-ray and radio emission peak, and another bright elliptical galaxy (BCG2) are also shown. Top right: ASKAP 856 MHz image of the Cloverleaf ORC convolved to 20 arcsec resolution. Bottom right: EPIC-pn flux image in the 0.5–1.2 keV band. The image is source-removed and smoothed by a 20" Gaussian kernel. Overlaid is the radio ASKAP contour of the Cloverleaf ORC (Koribalski et al., in prep.).


After filtering the flare time intervals, the clean exposure time is 21.6 ks.

2.2. Spectral analysis

We selected FLAG=0 events for spectral analysis within the 3' radius region surrounding the centroid of the two X-ray peaks
shown in Fig. 1. The background components consist of celestial X-ray photons and non-X-ray background (NXB) components. The former includes foreground emission from the Galactic Halo (GH) and cosmic X-ray background (CXB) as described in Bulbul et al. (2012). In addition to the XMM-Newton spectra, we extracted the combined spectrum (TM8) of the public eROSITA All-Sky Survey (eRASS1) observations in a region between 0.5–1 degree annulus centered on the Cloverleaf ORC by srctool in the eROSITA Science Analysis Software System (eSASS) software to constrain the foreground components and the contribution from the Milky Way halo to the background emission. The detected eRASS1 point and extended sources are masked when extracting the eRASS1 spectrum using the public catalogs (Bulbul et al. 2024; Merloni et al. 2024; Kluge et al. 2024).

We used the X-ray spectral fitting package (XSPEC) to co-fit the XMM-Newton and eROSITA spectra. All spectra were optically binned using $\text{ergs cm}^{-2}\text{s}^{-1}$ before loading into XSPEC (Kaastra & Bleeker 2016). The detailed configurations of the background model components are described in Appendix C. The four spectra were fit simultaneously to constrain the temperature of the diffuse X-ray emission and model the foreground and the particle background. We extracted a global spectrum using a 3′ aperture, including the northern and southern X-ray peaks. The low signal-to-noise PN observations did not allow a detailed study of the metal and temperature distribution of the system. Therefore, we froze the abundance to be 0.3 $Z_{\odot}$ for the rest of the spectral fits as typically assumed in galaxy clusters and groups (e.g., Bulbul et al. 2016; Mernier et al. 2018; Liu et al. 2020).

3. Results and discussion

The radio emission in the 856 MHz ASKAP image shows an elliptical boundary with a major axis of 2′ and 4′ (227 kpc) to a minor axis of 2.8′ (137 kpc) with an inclination angle of ~15° as plotted in the right panel of Fig. 1. The internal radio morphology clearly shows two peaks east of the ORC, 1 arcmin (55 kpc) apart from each other, with a shell-like emission surrounding the radio peaks. One of the two peaks is located at the position of the central galaxy. The detailed radio study of this ORC will be presented in Koribalski et al. (in prep.).

3.1. Properties of the diffuse gas

The new XMM-Newton observations show a clear diffuse X-ray emission at the location of the Cloverleaf ORC. The extended emission lies in the northeast direction perpendicular to the radio emission with a region size similar to a region approximately the size of an ellipse with axes of ~1.9′ (100 kpc) to 3.3′ (180 kpc). The X-ray morphology of diffuse gas shows two clear peaks; the central galaxy is located at the center of the southern peak, which also marks the location of the brightest radio emission. In contrast, the X-ray peak in the northeast direction is 1.8′ (98 kpc) from the southern peak and is not associated with a galaxy. The centroid of the X-ray emission (i.e., the center of the two X-ray peaks) is 37 kpc from the center of the two radio peaks and 80 kpc from the center of the radio ellipse. The southern peak also shows clear X-ray detection of an AGN in the center. The lack of the optical counterpart at the center of the northeastern X-ray peak and the disturbed morphology of the intragroup medium (IGrM) indicate that this system is in a non-relaxed dynamical state.

The X-ray spectroscopy provides measurements of the ambient gas temperature of the intragroup medium. The spectral fits adopting a single temperature scenario and free metal abundance yield a best-fit model with zero metallicity, suggesting a strong Fe-bias and the existence of a multi-temperature phase in the system (Simionescu et al. 2009). The best-fit temperature of the model is $kT_1 = 0.74 \pm 0.04 \text{keV}$ in a single-temperature scenario with a C-stat. value of 358.2/283. The two-temperature model significantly improves the spectral fit with components with $kT_1 = 1.10 \pm 0.08 \text{keV}$ and $kT_2 = 0.23 \pm 0.02 \text{keV}$ (C-stat. value of 277.9/281). The X-ray source, background spectra, and the two-temperature model fits are shown in Fig. 2. We also fit the individual spectra of the northeastern and southern X-ray emission. In a single-temperature model, the temperature of the northeastern X-ray peak is 0.75 ± 0.05 keV, and the southern peak has a slightly lower temperature of 0.31 ± 0.03 keV.

By fitting the azimuthally averaged X-ray surface brightness profile obtained from the XMM-Newton imaging analysis, we measure the central electron density to be $n_{e,0} = (4.9 \pm 0.6) \times 10^{-4} \text{cm}^{-3}$. From this, we measure the central electron number density to be $N_{e,0} = (5.0 \pm 0.6) \times 10^{21} \text{cm}^{-2}$.

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3.2. Dynamical state and the origin of the ORC

The catalogs in Kluge et al. (2024, see Appendix D) provide the photometric and spectroscopic redshifts of the galaxies in the literature in the western Galactic hemisphere. We search for galaxies with $|\Delta V| < 1000 \text{km s}^{-1}$ (5 × $\sigma_V$ of the group), around the Cloverleaf ORC. The location and their velocity dispersion are shown in Fig. 3. The projected spatial distribution of galaxies within this velocity range is elongated in an east–west orientation. A substructure on the northeast boundary of the radio emission has a velocity discrepancy with $>600 \text{km s}^{-1}$ from the central galaxy. This substructure is also identified as an individual galaxy group (ID 201611) in the catalog of G3Cv10 (Robotham et al. 2011).

By inspecting the morphology of individual galaxies in the DESI Legacy DR10 data (Dey et al. 2019), we find that three galaxies in the northeast of the central galaxy (A, B, and C in

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2 https://www.legacysurvey.org
Fig. 2. XMM-Newton spectrum of the Cloverleaf ORC is shown in black in the top panel. The best-fit two-temperature IGRM model is shown as blue and orange, while the foreground and background models are plotted as dashed lines. The bottom panels indicate good fits after the background modeling, including NXB with the foreground modeling of the eRASS1 data.

Fig. 3. Line-of-sight velocity structures of galaxies with $z_{\text{spec}}$ data within 30' angular distance. The dashed contour is the boundary of the radio emission. The inset is the histogram of $\Delta V$.

3.3. Comparison to other diffuse radio sources in groups and clusters

If the radio emission in the Cloverleaf ORC is caused by shock acceleration from merger shocks, it is worth comparing its properties to radio relics in galaxy clusters (e.g., Koribalski et al. 2023). Radio relics have powers of $\sim 10^{22}$ W Hz$^{-1}$ at 1.4 GHz, and their power is a strong function of the cluster mass (Jones et al. 2023). Their coincidence with X-ray-detected shock waves has suggested that they are caused by merger shocks where cosmic-ray electrons are accelerated with fairly high efficiencies (Botteon et al. 2020). These shocks are usually found well within the cluster virial radius and have a moderate sonic Mach number of $2-3$, unlike the cluster accretion shocks that sit outside the virial radius and have much higher Mach numbers.

In Fig. 4, we plot the radio luminosities of radio relics versus their mass. Here, we use the $M_{500}$ of the Cloverleaf group measured in Sect. 3.1. We also scale the radio power of the Cloverleaf ORC from the 856 MHz frequency to the LOFAR high-band antenna central frequency of 150 MHz by assuming $\alpha = 1$, which is the typical spectral index for radio relics in clusters (van Weeren et al. 2019). We find a mass difference of almost two orders of magnitude between the Cloverleaf ORC and known radio relics.

Radio relics are megaparsec-sized objects seen nearly edge-on; thus, radio power should decrease in smaller objects. This was confirmed by Dolag et al. (2023), who found that the high radio power observed in ORCs cannot be reproduced in numerical simulations. Reacceleration of fossil cosmic rays (CRs) could help reproduce the high observed radio power, as recently discussed by Shabala et al. (2024). These fossil cosmic rays could be injected by a central radio galaxy (e.g., powered by the AGN found in the Cloverleaf ORC). Then, the passage of a shock wave can sweep up the radio lobe and re-accelerate the plasma, creating the ORC. Shabala et al. (2024) discuss the combinations of viewing angles, angles between shock and radio lobe axis, as well as the age of the lobes that would lead to the observed ORC properties. This formation scenario also naturally explains the rarity of ORCs since only fairly narrow ranges in lobe ages and geometric factors lead to observable ORCs. Future simulations, including the role of magnetic fields, will have to explore this possibility. This scenario might also be validated by radio observations at very low radio frequencies that may detect the emission of remnant lobes.

The high radio power also suggests high magnetic field strengths, and, for reference, we can estimate the equipartition magnetic field. If the radio emission is homogeneous within the volume of the Cloverleaf ORC, the source depth is the average length of the long and short axes, which is 360 kpc. Meanwhile, we use the radio surface brightness close to the edge for a lower limit estimate. We estimate a minimum energy density contained in cosmic rays (CRs) of $\rho_{\text{min,CR+B}} = 3.2 \times 10^{-14}$ erg cm$^{-3}$. 

Fig. 4. Diagram of radio power vs. halo mass for the samples of radio relics (Jones et al. 2023) and central radio galaxies (Pasini et al. 2022) observed by LOFAR and the Cloverleaf ORC. The power of the Cloverleaf ORC is converted to the frequency of 150 MHz by assuming a $\alpha = 1$ spectral index. The error bar of the Cloverleaf ORC radio power is within the mark.

Govoni & Feretti (2004), adopting $\alpha = 1$. The corresponding revised magnetic field strength at equipartition is therefore $B_{eq} = 1.2 \mu G$ by assuming $\gamma_{\min} = 100$ (Brunetti et al. 1997; Beck & Krause 2005). Both $\gamma_{\min}$ and $B_{eq}$ are higher if we adopt steeper spectral indices. The estimated 1.2 $\mu G$ equipartition magnetic field strength results in a magnetic pressure of $P_B = B^2/8\pi \sim 3.6 \times 10^{-5}$ keV cm$^{-3}$. For comparison, the thermal pressure in the hot IGrM can be calculated as $P_{th} = n_k T \sim 6.9 \times 10^{-4}$ keV cm$^{-3}$, taking the central gas density as an upper limit. The ratio of the thermal and magnetic pressures, $p_{th}/p_{B} = p_{th}/p_{B}$, is $\beta_{PL} \sim 20$ compared to $>100$ in typical galaxy clusters (Donnert et al. 2018). However, we also note that in galaxy clusters, magnetic field strengths are around 1/20th of the equipartition field (Berentsen 1999).

4. Conclusions

This work presented the first detection of diffuse X-ray emission from a recently discovered Cloverleaf odd radio circle. The extended X-ray source with an extent of 100 kpc by 180 kpc lies in the northeast direction perpendicular to the radio emission. The disturbed morphology of the intra-group medium, the high-velocity subgroup identified at optical wavelengths, and the disturbed morphologies of galaxies toward the east around the Cloverleaf ORC suggest that this system is undergoing a merger activity. The absence of the central galaxy of the northeastern peak does not have an optical counterpart or correspond to any radio peak. The open性 between the centroid of the radio emission and radio emission is 80 kpc.

The X-ray emission has a thermal nature, where the average density of the gas is $(7.0 \pm 1.8) \times 10^{-5}$ cm$^{-3}$ within $R_{500}$, which is lower than typically observed in galaxy groups (Bahar et al. 2024). We measure the central electron density to be $(4.9 \pm 0.6) \times 10^{-4}$ cm$^{-3}$. The temperature measurements of the gas indicate that it is in a multi-phase state with components of $1.1 \pm 0.08$ keV and $0.23 \pm 0.02$ keV. The corresponding gas and total masses are $(7.7 \pm 0.8) \times 10^{11} M_\odot$ and $(2.6 \pm 0.3) \times 10^{11} M_\odot$ within the overdensity radius of $R_{500}$ of 446 $\pm$ 40 kpc, inferred from the X-ray observations under the hydrostatic equilibrium and isothermal IGM assumptions. The flux and luminosity of the ORC are $(2.3 \pm 0.2) \times 10^{32}$ erg s$^{-1}$ cm$^{-2}$ and $(1.3 \pm 0.1) \times 10^{32}$ erg s$^{-1}$ measured within the same radius. The properties of the diffuse X-ray thermal gas indicate that the Cloverleaf ORC lies in an intra-group environment.

The disturbed morphology of the intra-group medium, the high-velocity subgroup identified at optical wavelengths, and the disturbed morphologies of galaxies toward the east around the Cloverleaf ORC suggest that this system is undergoing a merger activity. The absence of the central galaxy of the northeastern gas component may indicate that the collisionless member galaxies have already left behind the highly collisional intra-group medium. Such large offsets between the galaxy and X-ray gas are commonly observed in major galaxy cluster mergers (Markevitch et al. 2004).

If the elliptical morphology of radio emission has a shock origin, comparing the radius of radio emission of the ORC ($\sim 200$ kpc) and the virial radius of the galaxy group $\sim 680$ kpc, the merger shock is the most likely explanation of the observed multiwavelength properties of this object. With eight known ORCs, any explanation of their origin must explain why they are rare. Dolag et al. (2023) argue that the galaxy mergers that produce ORCs must lead to a dramatic increase in the halo mass (by a factor of $\sim 3$), which can explain why so few are seen. Moreover, there may be further constraints on the angle between the main merger axis and the line of sight, making them rarer still.

Our results indicate that, for the Cloverleaf ORC, merger shocks in galaxy group size halos are the most likely origin for the radio emission. To explain its high radio luminosity, a scenario that involves remnant radio lobes of a supermassive black hole, as discussed in Shabala et al. (2024), is plausible.

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Appendix A: Assumed cosmology

In this work we adopt a Λ-cold-dark-matter cosmology with parameters $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$. At $z = 0.0464$, one arcsecond corresponds to a physical scale of 0.91 kpc.

Appendix B: Imaging analysis

For extracting the image, we selected (FLAG & 0xfb0825) !=0 && PATTERN < 4 events. We adopted the cooling function in the [0.5, 1.2] × (1 + z) keV band at the system’s average temperature to convert the density to projected surface brightness.

Appendix C: Spectral analysis and models

Energy ranges, including fluorescent instrumental lines in the energy bands of 1.3–1.7 keV, 4.4–5.7 keV, and 7–11 keV, were ignored in the PN fittings. We used C-stat to calculate the fitting statistics (Cash 1979) and adopted the solar abundance table from Asplund et al. (2009).

The components in different spectra are listed in Table C.1. Among them, the components of celestial X-ray photons are convolved by the redistribution matrix file (RMF) and folded by the ancillary response file (ARF) for model calculation; components of particle background and Out-of-Time (OoT) are only convolved by the RMF for model calculation. The CXB includes 6.3% of OoT events and particle backgrounds whose spectra were generated from OoT event files and the stacked filter-wheel-closed (FWC) event file, respectively.

The detailed XSPEC spectral model definition of each component is listed in Table C.2. The redshifts of the source APEC models are fixed to 0.046; the hydrogen column density of the tbabs models are fixed to $2.3 \times 10^{20}$, which includes the contribution from both neutral hydrogen and molecular hydrogen (Willingale et al. 2013). The redshifts of both the Local Hot Bubble (LHB) and GH APEC models are fixed to zero. The abundance of the LHB APEC is fixed to 1.0 while that of the GH APEC model is set to be free, given the recent $\sim 0.06 Z_\odot$ measurement reported by Ponti et al. (2023). Because we already ignored the energy ranges of instrumental lines, we modeled the pn FWC spectrum using a bkg2pow model. We used a free constant parameter to scale the pn FWC normalization to the particle background level in the observed spectrum. The pn OoT spectrum is a highly smoothed source spectrum, which can be well fitted empirically using a bkg2pow model (see the fitting residual of the OoT spectrum in Fig. 2). The FWC spectral model was provided by Yeung et al. (2023), which is publicly available on the eROSITA DR1 site.

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<th>Spectrum</th>
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<td>EPIC-pn</td>
<td>SRC + FG + CXB-XMM</td>
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<tr>
<td>EPIC-pn OoT</td>
<td>0.063×OOT + constant×FWC-pn</td>
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<tr>
<td>EPIC-pn FWC</td>
<td>OOT</td>
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<tr>
<td>eRASS:1 TM8 local background</td>
<td>FG + CXB-eRASS</td>
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<th>Table C.2. Spectral model for each component.</th>
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<td>SRC</td>
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<td>FWC-TM8</td>
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3 https://www.cosmos.esa.int/web/xmm-newton/filter-closed
4 https://erosita.mpe.mpg.de/dr1/AllSkySurveyData_dr1/FWC_dr1/
### Appendix D: Averaged surface brightness profile

![Graph showing surface brightness profile](image)

**Fig. D.1.** Azimuthally averaged surface brightness profiles (purple), subtracted NXB (green), and best-fit model profile (purple step). The models of the individual components, i.e., the IGrM and X-ray foreground and background, are plotted as orange steps and dotted gray lines, respectively.

We plot the azimuthally averaged surface brightness profile as well as the best-fit models in Fig. D.1.

### Appendix E: Morphology of Galaxy A

![Image of galaxy A](image)

**Fig. E.1.** Cutout of the Legacy Surveys $g$-band image around galaxy A (left) and residual after subtracting an isophotal model. North is up; east is left.

We note an asymmetric feature in the stellar light of galaxy A in Figure E.1, left panel. The disk is slightly warped. The residual image, after subtracting an isophotal model, enhances this feature in the south by revealing an extension toward the south-west. The isophotal model was created following the procedure described in Kluge & Bender (2023).