

Galaxy Cluster Diffuse Radiation Research Post-print

Authors: Xie Yushan^{1,2,3}, He Mengfan^{1,2,3}, Mao Yufeng⁴, Zheng Qian², Shan Huanyuan^{2,3}, Guo Quan²

Date: 2023-06-07T00:00:00+00:00

Abstract

Diffuse emission in galaxy clusters typically manifests as radio halos located in the central region or radio relics in the peripheral regions. Based on the steep-spectrum characteristics of diffuse emission in galaxy clusters, observations in the broadband low-frequency radio band can yield the spectral features of radio halos and radio relics therein, thereby aiding in understanding the formation and evolution of galaxy clusters. By analyzing radio-band observational data from the Murchison Widefield Array (MWA) and the Australia Telescope Compact Array (ATCA) for galaxy cluster SPT J2201-5956 at redshift $z = 0.098$ and galaxy cluster SPTJ2023-5535 at $z = 0.232$, the diffuse emission properties of these two galaxy clusters were obtained. The analysis results indicate that the spectral index of diffuse emission in SPT J2201-5956 is $-1.68+0.27-0.27$, with its origin possibly being dead galaxies in the cluster; the spectral index of diffuse emission in SPT J2023-5535 is $-1.21+0.02-0.02$, and its emission is located in the central region of the galaxy cluster, thus the diffuse source in this cluster can be considered a radio halo candidate.

Full Text

Preamble

Progress in Astronomy, Vol. 39, No. 3, September 2021
doi: 10.3969/j.issn.1000-8349.2021.03.06

Research on Diffuse Emission in Massive Galaxy Clusters

XIE Yushan^{1;2;3}, HE Mengfan^{1;2;3}, MAO Yufeng⁴, ZHENG Qian², SHAN Huanyuan^{2;3}, GUO Quan²

(1. National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100101, China;

2. Shanghai Astronomical Observatory, Chinese Academy of Sciences, Shanghai

200030, China;

3. University of Chinese Academy of Sciences, Beijing 100049, China;

4. Bureau of Frontier Sciences and Education, Chinese Academy of Sciences, Beijing 100864, China)

Abstract

Diffuse emission in galaxy clusters typically manifests as radio halos in central regions or radio relics in peripheral regions. Based on the steep-spectrum characteristics of cluster diffuse emission, broadband low-frequency radio observations can reveal the spectral properties of radio halos and relics, thereby aiding our understanding of galaxy cluster formation and evolution. By analyzing observational data from the Murchison Widefield Array (MWA) and the Australia Telescope Compact Array (ATCA) for the galaxy clusters SPT J2201-5956 at redshift $z = 0.098$ and SPT J2023-5535 at $z = 0.232$, we have determined the diffuse emission properties of these two clusters. Our analysis indicates that the diffuse emission in SPT J2201-5956 has a spectral index of -1.68 ± 0.27 , likely originating from dead galaxies within the cluster, while the diffuse emission in SPT J2023-5535 has a spectral index of -1.21 ± 0.02 and is located in the cluster's central region, suggesting it is a radio halo candidate.

Keywords: interferometry; galaxy clusters; diffuse emission; spectral index

1 Introduction

Galaxy clusters, composed of hundreds to thousands of galaxies permeated by intracluster medium, represent the largest gravitationally bound systems in the universe. When cosmic rays and protons are accelerated through cluster magnetic fields, they produce diffuse synchrotron radio emission that exists in two possible forms: radio halos in central regions or radio relics in the periphery. The generation of these two types of diffuse radio sources is intimately connected with cluster dynamical processes, particularly cluster mergers: radio halos are generally considered the result of turbulent motions in cluster centers [1], while radio relics are produced by low-Mach-number shocks propagating through the intracluster medium during mergers [2].

The diffuse radio emission in galaxy clusters exhibits very steep spectra, with spectral indices α ($S \propto \nu^{-\alpha}$) typically ranging from -2.3 to -1.0. This spectral characteristic causes radio signals to weaken significantly at high frequencies while remaining readily detectable at low frequencies, making low-frequency radio bands crucial for studying diffuse cluster emission. Although numerous radio halos and relics have been observed in galaxy clusters, relatively few studies have examined their spectral distribution properties across a broad frequency range (from hundreds of MHz to GHz). Observing individual clusters across radio frequencies and investigating their spectral properties—such as in the Coma Cluster, A521, and A3562 [3]—advances research on radio halos and relics, helps understand the physical mechanisms during cluster mergers, and ultimately im-

proves our comprehension of galaxy cluster and cosmic formation and evolution. Consequently, observing cluster radio signals has become a primary scientific objective for many radio interferometric arrays, including the Low Frequency Array [4] (LOFAR), the Giant Metrewave Radio Telescope [5] (GMRT), and MWA [6, 7]. Notably, these low-frequency arrays can detect steep-spectrum targets observable only at low radio frequencies, such as Macario et al. [8] using GMRT at 150 MHz to observe cluster A697, revealing a radio relic from a shock in the northwest direction with spectral indices between -0.9 and -0.7, while also discovering a megaparsec-scale radio halo with spectral indices from -2.3 to -1.0.

MWA conducted low-frequency radio observations of 224 SPT clusters, with 24 showing diffuse emission. This paper focuses on analyzing observational data from two massive merging clusters, SPT J2201-5956 and SPT J2023-5535, to investigate the properties of intracluster diffuse radio emission. SPT J2201-5956 (22h01min53.3s, -59°56'43"), *located at redshift $z = 0.098$, is a massive cluster in a late merger stage, with low-frequency diffuse emission extending approximately* Bulbul et al. [11] used XMM-Newton data to study this cluster's X-ray properties and fit relationships between cluster mass and X-ray luminosity. HyeonHan et al. [12] used ASKAP-EMU [13] to observe SPT J2023-5535 at radio wavelengths, detecting a $1 \text{ Mpc} \times 0.5 \text{ Mpc}$ radio halo and a $\sim 0.5 \text{ Mpc}$ radio relic.

Section 2 describes the observational data and processing methods for the telescopes (MWA: 120–260 MHz, ATCA: 2.1 GHz and 4.8 GHz). Section 3 presents detailed analysis of the radio emission properties in SPT J2201-5956 and SPT J2023-5535, providing spectral indices for the diffuse emission and discussing possible formation mechanisms. Section 4 offers a brief summary. The cosmological parameters used in this paper are $H_0 = 73 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$, $\Omega_m = 0.27$, $\Omega_\Lambda = 0.73$.

2.1 MWA Data

The Murchison Widefield Array operates at 70–300 MHz. This study uses data from MWA Phase I. Tingay et al. [7] provide detailed descriptions of MWA Phase I antenna design and configuration; we summarize here: MWA Phase I consists of 128 tiles distributed over a $\sim 3 \text{ km}$ diameter area. Each tile contains 16 dipole antennas arranged in a 4×4 configuration, enabling polarization measurements for both “X” (16 east-west dipoles) and “Y” (16 north-south dipoles). The numerous antennas and tiles ensure excellent uv coverage, permitting good beamforming even with short observation times. Additionally, MWA's advantage includes an extremely wide field of view (610 square degrees at 150 MHz), meaning a single observation can cover numerous celestial objects. GLEAM [14] (GaLactic and Extragalactic All-sky MWA survey) is a southern sky survey conducted by MWA across 72–231 MHz, with galaxy cluster research as a key scientific goal. This paper uses GLEAM observational data for low-frequency radio imaging and flux density measurements of our target clusters.

Hurley-Walker et al. [15] detail MWA data processing methods, which serve as our reference pipeline. Raw visibilities are first processed through Aoflagger [16] to remove radio frequency interference, then phase and flux calibrated for each observation-antenna-polarization-frequency band using selected calibrators within the observed field (e.g., PKS 0408-65), and finally imaged using CLEAN.

For cluster SPT J2201-5956, we selected four sub-band GLEAM raw datasets with central frequencies at 120 MHz, 150 MHz, 180 MHz, and 215 MHz. During processing, we employed robust weighting of 0 and imaged each band. SPT J2023-5535 data originate from Hindson et al. [17] observations of A3667 (near J2023-5535). We used Hindson et al.'s processed data with robust weighting of +1.0, imaging four sub-bands with 30.72 MHz bandwidth at central frequencies of 120 MHz, 149 MHz, 180 MHz, and 226 MHz. Table 1 presents the observational properties of the two clusters' images across different frequencies.

2.2 ATCA Data

The Australia Telescope Compact Array, located in northwestern New South Wales, Australia, is a radio array comprising six 22 m antennas. Data for SPT J2201-5956 and SPT J2023-5535 at 2.1 GHz come from 2013 observations (PI: Melanie Johnston-Hollitt), utilizing three ATCA configurations: 6A, 750D, and EW352, with a central frequency of 2.1 GHz and bandwidth of 2048 MHz. Table 2 provides detailed ATCA observational information used in this paper.

Cluster data were processed using MIRIAD [18], similar to CABB [19] (compact array broadband backend) processing. Edge frequency channels within the bandpass rolloff region were flagged; data were then divided into four sub-bands (central frequencies: 1332 MHz, 1844 MHz, 2356 MHz, and 2868 MHz) for individual calibration and imaging. For both clusters, PKS B1934-638 served as bandpass and flux calibrator, while PKS B2117-642 was the phase calibrator during 2.1 GHz observation calibration. Imaging employed robust weighting of 1 and standard deconvolution using the Steer clean algorithm (3σ) to obtain Stokes I images. Given the large spatial scales of diffuse sources in clusters, short-baseline observations are most suitable; therefore, the longest baselines (6 km) were excluded when using ATCA data to detect cluster diffuse sources. At higher frequencies (4.8 GHz), uv coverage degrades while diffuse source signals rapidly weaken, making ATCA's point source detection capability relatively enhanced; consequently, high-resolution array configurations (considering only 6 km baselines) were used for point source detection.

For cluster SPT J2023-5535, we added ATCA observational data at 4.8 GHz from the Australia Telescope Online Archive (ATOA). The 4.8 GHz data processing followed the same procedure as for 2.1 GHz, with PKS B1934-638 as primary calibrator and IERS B2117-614 as secondary calibrator. Four sub-bands had central frequencies of 4732 MHz, 5244 MHz, 5756 MHz, and 6268 MHz.

Table 3 presents ATCA image properties at both frequencies (2.1 GHz and 4.8 GHz). Additionally, we used the 843 MHz radio catalog from the Sydney

University Molonglo Sky Survey [20, 21] (SUMSS) to help identify and subtract point sources in SPT J2023-5535.

2.3 X-ray Data

The Chandra X-ray Observatory observed cluster SPT J2201-5956 (observation date: 2007-08-20, ObsID: 7920, exposure time: 50.0 ks) and cluster SPT J2023-5535 (observation date: 2014-03-30, ObsID: 15108, exposure time: 20.81 ks). We downloaded the target clusters' X-ray raw data from the Chandra database and processed them using the official software CIAO (<http://cxc.cfa.harvard.edu/ciao/>, version 4.9) and CALDB v4.6.2. Raw data were calibrated using the "chandra_{repro}" tool, creating files with calibration flag equal to 2. The tool "lc_{clean}" removed observation times affected by solar activity and other contaminants; finally, the "fluximage" tool recreated images with corrected effective exposure times in the soft X-ray band (0.5-2.0 keV). Bright sources were detected using "celldetect," manually inspected, and removed using "dmfilth."

3 Study of Radio Diffuse Emission in Galaxy Clusters

Based on the above data processing, we obtained cluster images at various wavelengths to investigate the properties of cluster radio diffuse emission.

3.1.1 Spectral Characteristics of Cluster Diffuse Emission

Figure 1 [Figure 1: see original paper] presents images of SPT J2201-5956 in four MWA frequency bands, revealing large-scale diffuse emission at the cluster center.

To accurately measure diffuse emission in the images, point source contamination must first be removed. Considering angular resolution and uv coverage limitations, discrete point sources were identified using only high-resolution observations with 6 km baselines and the highest frequency data to achieve maximum resolution. Two point sources were identified within the cluster spatial region covered by MWA images: Source 1 (22h03min1.95s, -59°56' 18.41") and Source 2 (22h01min49.33s, -59°55' 34.69"). After determining source positions, we measured fluxes S for each point source using four sub-bands from low-resolution ATCA images: $S_{1332} = 1.26$ mJy, $S_{1844} = 0.82$ mJy; $S_{2356} = 1.15$ mJy, $S_{2868} = 1.11$ mJy, where subscripts denote source 1 or 2 and superscripts indicate the central frequency of each band. Due to insufficient uv coverage, we could not accurately measure Source 2's flux in the two lower-frequency images, so these low-frequency measurement points were excluded from spectral index fitting. Using $S \propto \nu^{-\alpha}$ and measured point source fluxes, we fitted spectral indices of $\alpha_1 = -0.60$ and $\alpha_2 = -0.20$.

ATCA images have higher resolution than MWA images, enabling foreground point source identification and spectral index determination within the ATCA

frequency range, while MWA clearly detects large-scale diffuse emission. By integrating flux density within the cluster spatial region in MWA images, we obtained total flux. Extrapolating point source fluxes to MWA frequencies based on their spectral indices and subtracting from total flux yielded the integrated flux density of diffuse emission. We adopted a 20% error for diffuse emission flux measurements to account for MWA image flux calibration errors and ATCA uv coverage deficiencies.

In addition to MWA and ATCA data, we incorporated 408 MHz Molonglo images for this cluster. Following the same procedure as for MWA images—subtracting point source radiation from total image flux—we obtained diffuse source flux with a 10% error estimate.

Assuming the same power-law relationship $S \propto \nu^{-\alpha}$ for diffuse source flux and spectral index as for point sources, we performed fits in logarithmic space: before point source subtraction, the cluster's spectral index across MWA frequencies was $\alpha = -1.61 \pm 0.27$; after point source subtraction, the cluster's spectral indices were $\alpha = -1.68 \pm 0.27$ (without Molonglo data) and $\alpha = -1.17 \pm 0.10$ (including Molonglo data). Including the 408 MHz Molonglo data in the fit changed the spectral index to $\alpha = -1.32 \pm 0.09$.

3.1.2 Origin of Cluster Radio Diffuse Sources

Brunetti et al. [22] proposed that radio halos dominate at lower frequencies compared to radio relics because halos have steeper spectra with $\alpha \approx -1.5$. In the previous section, we measured a spectral index of $\alpha = -1.68 \pm 0.27$ for the radio diffuse emission in SPT J2201-5956, with its projected position in the cluster central region, suggesting the diffuse source may be a large-scale radio halo. We further investigated relationships between radio halo power and X-ray luminosity L_x and total cluster mass M_{500} : $L(0.1-2.4 \text{ keV}) = 2.1 \times 10^{37} \text{ J} \cdot \text{s}^{-1}$ [23], $M_{500} = (4.30 \pm 0.28) \times 10^{14} \text{ M}$. From the spectral index, we derived a radio diffuse emission power at 1.4 GHz of $P_{1.4} = 5.31 \times 10^{22} \text{ W} \cdot \text{Hz}^{-1}$. Cassano et al. [24] proposed a simple power-law relationship between radio halos and X-ray luminosity: $\lg(P_{1.4}) = A + B \lg(L)$. Fitting radio emission from 61 clusters including SPT J2201-5956 yielded halo fitting parameters $(A, B) = (-27.85, 1.16)$. Cassano et al. [24] also proposed an alternative relationship: $\lg(P_{1.4}) = A + B \lg(M_{500})$, giving fitting parameters $(A, B) = (-17.98, 2.85)$ for radio halos in 52 clusters including SPT J2201-5956.

Figure 2 [Figure 2: see original paper] overlays radio observations at different frequencies (170-231 MHz MWA, 843 MHz SUMSS, 408 MHz Molonglo, and 2868 MHz ATCA) on an optical image (SuperCOSMOS). The radio diffuse emission in SPT J2201-5956 appears approximately bilaterally symmetric on both sides, with two sub-structures at similar distances from the cluster center: $239.29 \text{ h}^{-1} \text{ kpc}$ and $193.39 \text{ h}^{-1} \text{ kpc}$. Therefore, the diffuse source cannot be ruled out as radio relics, with the northeastern relic ($>1.75 \text{ mJy}$ at 1844 MHz) brighter than the southwestern relic ($>1.19 \text{ mJy}$).

When diffuse radio emission in clusters exhibits a two-lobed distribution with steep spectra, its formation may relate to dead radio galaxies. AGN supply energy to radio sources in elliptical galaxies through plasma; once this energy supply ceases, the radio source enters a decay phase. During decay, the absence of a radio core, jets, or hotspots reveals radio plasma from earlier activity periods, producing very steep-spectrum radio radiation with spectral index α typically less than -1.5. The diffuse radio emission in SPT J2201-5956 shows no cores, jets, or hotspots, with a spectral index of -1.68 ± 0.27 , strongly suggesting a dead galaxy origin. We recalculated the 1.4 GHz radio power for galaxies from Hurley-Walker et al. [25] Figure 5 [Figure 5: see original paper], shown in Figure 3 [Figure 3: see original paper], including the power-size diagram for radio galaxies with SPT J2201-5956. Compared to typical FR-I and FR-II radio galaxies [26], giant radio galaxies (GRG) discovered by Schoenmakers et al. [27] and Sault et al. [18], and GRGs associated with NGC 1534 [25], the radio lobes in SPT J2201-5956 are extremely faint, consistent with dead galaxy characteristics. Considering the scale, polarization, presence/absence of cores, optical counterparts, and other features of the radio emission in SPT J2201-5956 (summarized in Table 4), we conclude that the detected large-scale diffuse radio emission likely originates from a dead radio galaxy.

3.2.1 Spectral Characteristics of Diffuse Emission in SPT J2023-5535

We further analyzed SPT J2023-5535 using MWA and ATCA data, shown in Figure 4 [Figure 4: see original paper], where ATCA 2.1 GHz, 4.8 GHz, and MWA images were convolved with Gaussian functions of FWHM $60'' \times 60''$, $150'' \times 150''$, and $351'' \times 254''$ respectively.

Consistent with Section 3.1.1, we first considered point source subtraction when detecting radio diffuse emission in SPT J2023-5535. Combining high-resolution 2.1 GHz ATCA images and the 843 MHz SUMSS radio catalog, we identified four point sources within the cluster's diffuse emission region at coordinates $(20^{\text{h}}22^{\text{m}}58.1^{\text{s}}, -55^{\circ}37'4.9'')$, $(20^{\text{h}}23^{\text{m}}19.3^{\text{s}}, -55^{\circ}36'3.0'')$, $(20^{\text{h}}23^{\text{m}}39.2^{\text{s}}, -55^{\circ}33'56.8'')$, and $(20^{\text{h}}23^{\text{m}}47.0^{\text{s}}, -55^{\circ}33'47.1'')$. To obtain the final diffuse source flux in the cluster, we used DUCHAMP [29] to fit point source fluxes. The high-resolution 2.1 GHz ATCA image and SUMSS enabled fitting all four point sources, with additional 4.8 GHz ATCA data included. However, due to short observation time and limited uv coverage at 4.8 GHz, only one bright source's flux could be measured.

Spectral index fitting after flux measurement yielded $\alpha = -1.08 \pm 0.03$, $\alpha = -1.51 \pm 0.07$, $\alpha = -1.09 \pm 0.06$, and $\alpha = -0.67 \pm 0.07$ for the four point sources in SPT J2023-5535. Comparing with the NASA/IPAC Extragalactic Database (NED), our flux measurements at 843 MHz for Sources 1, 3, and 4 are consistent, while Source 2's flux is lower than NED records due to insufficient image resolution introducing observational errors.

Extrapolating the four point sources' fluxes to MWA and ATCA 4.8 GHz fre-

quencies and subtracting them from images yielded the diffuse emission flux in SPT J2023-5535. Due to MWA's low resolution and incomplete flux calibration accuracy, we adopted a 20% flux error; ATCA's uv coverage limitations introduce flux measurement errors set at 10%; SUMSS image flux errors were also set at 10%. Final flux calculations and fitting gave a spectral index of $\alpha = -1.17 \pm 0.02$ before point source subtraction across 120 MHz–6268 MHz. After point source subtraction, assuming a simple power-law relationship between flux and spectral index yielded $\alpha = -1.21 \pm 0.02$. However, we found a spectral break between low-frequency MWA data and high-frequency ATCA data; assuming a constant spectral index would underestimate flux density in MWA images. When considered separately, the spectral index from MWA data is $\alpha_{\{MWA\}} = -0.78 \pm 0.06$, while ATCA data give $\alpha_{\{ATCA\}} = -1.47 \pm 0.03$.

3.2.2 Theoretical Models

This section compares the measured spectral energy distribution of diffuse emission in SPT J2023-5535 with theoretical models for radio relics and halos.

Theoretically, cluster mergers generate shocks at cluster boundaries and in large-scale filamentary structures; shock propagation through the intracluster medium ultimately produces radio relics. Using the radio relic theoretical model from Enßlin and Gopal-Krishna [30], we fitted the diffuse source in SPT J2023-5535, obtaining an electron spectral index $\alpha_e = 2.67$. The fit between diffuse source and radio relic model is shown in Figure 5 [Figure 5: see original paper]. Observations indicate SPT J2023-5535's magnetic field is on the order of 10^{-10} T; considering observational errors we assume $B = 10^{-10}$ T, and theoretical calculations from Enßlin and Gopal-Krishna [30] give a maximum electron momentum $p^* = 10^5$ in the cluster diffuse emission.

Schlickeiser et al. [31] and Thierbach et al. [32] studied radio halo models using the Coma cluster, proposing an in-situ model where relativistic electron acceleration balances energy losses in the intracluster medium. We applied the same in-situ model to fit the diffuse emission in SPT J2023-5535, which has two free parameters Γ and ν_s . The model predicts a power-law radio halo spectrum with a cutoff at high frequencies, where ν_s is the cutoff frequency and Γ is the spectral index before cutoff. For SPT J2023-5535, fitting yielded $\Gamma = 4.34 \pm 0.13$ and $\nu_s = 1.23 \pm 0.26$ GHz, consistent with Thierbach et al. [32] results ($\Gamma = 4.6 \pm 0.8$, $\nu_s = 0.44 \pm 0.28$ GHz). Figure 6 [Figure 6: see original paper] shows the diffuse emission fit using the radio halo model.

These discussions show that the radio diffuse emission in SPT J2023-5535 is consistent with both radio relic and radio halo theoretical models. However, as shown in Figure 7 [Figure 7: see original paper], X-ray images reveal the cluster center location, and the cluster's diffuse emission is also distributed in the central region, leading us to conclude that the diffuse emission in SPT J2023-5535 is a radio halo candidate.

4 Summary and Outlook

Due to the steep-spectrum nature of cluster diffuse emission, low-frequency radio bands are more favorable than other wavelengths for observing and studying cluster diffuse emission, thereby deepening our understanding of radio halo and relic properties. Through MWA and ATCA observations of massive clusters SPT J2201-5956 and SPT J2023-5535, we obtained the spatial distribution and spectral indices of their radio diffuse emission. Based on the spectral characteristics of cluster diffuse sources, we further combined possible models to fit the diffuse emission and discuss its origin. Our analysis suggests the diffuse emission in SPT J2201-5956 likely originates from dead galaxies, while the diffuse emission in SPT J2023-5535 may be a radio halo candidate located in the cluster center.

MWA's insufficient resolution prevents identification of discrete point sources in clusters, while ATCA's limited uv coverage cannot fully detect cluster diffuse emission. Therefore, this paper combines MWA and ATCA for radio emission detection. Future understanding of cluster diffuse emission requires telescopes with better uv coverage and higher resolution. Currently, MWA Phase II is operational with significantly improved resolution and sensitivity, making it more suitable for diffuse source studies. In coming years, LOFAR [4] and MWA are expected to conduct series of survey observations, providing opportunities to detect more cluster radio diffuse sources. Furthermore, the SKA [33] era will substantially enhance observational sensitivity, enabling not only more precise observations of individual radio sources but also dramatically increasing the number density of observable sources, allowing statistical measurements of diffuse radio emission.

References

- [1] Miniati F. *ApJ*, 2015, 800(1): 60
- [2] van Weeren R J, de Gasperin F, Akamatsu H, et al. *Space Sci. Rev.*, 2019, 215(1): 16
- [3] Giacintucci S, Venturi T, Brunetti G, et al. *A&A*, 2005, 440: 867
- [4] van Haarlem M P, Wise M W, Gunst A W, et al. *A&A*, 2013, 556: A2
- [5] Swarup G. *IAU Colloq.* 131, 1991, 19: 376
- [6] Lonsdale C J, Cappallo R J, Morales M F, et al. *IEEE Proceedings*, 2009, 97: 1497
- [7] Tingay S J, Goeke R, Bowman J D, et al. *PASA*, 2013, 30: e007
- [8] Macario G, Venturi T, Dallacasa D, et al. *Mem. Soc. Astron. Italiana*, 2011, 82: 557
- [9] Williams L L R, Saha P. *MNRAS*, 2011, 415: 448
- [10] Massey R, Williams L, Smit R, et al. *MNRAS*, 2015, 449: 3393
- [11] Bulbul E, Chiu I N, Mohr J J, et al. *ApJ*, 2019, 871(1): 50
- [12] HyeonHan K, Jee M J, Rudnick L, et al. *ApJ*, 2020, 900(2): 127
- [13] Norris R P, Hopkins A M, Afonso J, et al. *PASA*, 2011, 28(3): 215
- [14] Wayth R B, Lenc E, Bell M E, et al. *PASA*, 2015, 32: e025

- [15] Hurley-Walker N, Morgan J, Wayth R B, et al. PASA, 2014, 31: e045
- [16] Offringa A R, Wayth R B, Hurley-Walker N, et al. PASA, 2015, 32: e008
- [17] Hindson L, Johnston-Hollitt M, Hurley-Walker N, et al. MNRAS, 2014, 445: 330
- [18] Sault R J, Teuben P J, Wright M C H. Astronomical Data Analysis Software and Systems IV, 1995, 77:
- [19] Wilson W E, Ferris R H, Axtens P, et al. MNRAS, 2011, 416(2): 832
- [20] Bock D C J, Large M I, Sadler E M. AJ, 1999, 117: 1578
- [21] Mauch T, Murphy T, Buttery H J, et al. MNRAS, 2003, 342: 1117
- [22] Brunetti G, Giacintucci S, Cassano R, et al. Nature, 2008, 455: 944
- [23] Carrasco E R, Gomez P L, Verdugo T, et al. ApJ, 2010, 715(2): L160
- [24] Cassano R, Etori S, Brunetti G, et al. ApJ, 2013, 777: 141
- [25] Hurley-Walker N, Johnston-Hollitt M, Ekers R, et al. MNRAS, 2015, 447: 2468
- [26] Laing R A, Riley J M, Longair M S. MNRAS, 1983, 204: 151
- [27] Schoenmakers A P, de Bruyn A G, Röttgering H J A, et al. A&A, 2001, 374: 861
- [28] Saripalli L, Hunstead R W, Subrahmanyan R, et al. AJ, 2005, 130(3): 896
- [29] Whiting M T. MNRAS, 2012, 421: 3242
- [30] Enßlin T A, Gopal-Krishna. A&A, 2001, 366: 26
- [31] Schlickeiser R, Sievers A, Thiemann H. A&A, 1987, 182: 21
- [32] Thierbach M, Klein U, Wielebinski R. A&A, 2003, 397: 53
- [33] Ekers R. <http://www.arxiv.org/abs/1212.3497>, arXiv:1212.3497, 2012

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv – Machine translation. Verify with original.