CHANG-ES. XXIV. First Detection of a Radio Nuclear Ring and Potential LLAGN in NGC 5792

Yang Yang (杨阳)1, Judith Irwin2, Jiangtao Li3, Theresa Wiegert2, Q. Daniel Wang4, Wei Sun5, A. Damas-Segovia6, Zhiyuan Li7,8, Zhiqiang Shen1,9, René A. M. Walterbos10, and Carlos J. Vargas11

1 Shanghai Astronomical Observatory, Chinese Academy of Sciences, 80 Nandan Road, Shanghai 200030, People’s Republic of China; yangyang.astro@gmail.com
2 Department of Physics, Engineering Physics & Astronomy, Queens University, Kingston, Ontario, K7L 3N6, Canada
3 Department of Astronomy, University of Michigan, 311 West Hall, 1085 South University Avenue, Ann Arbor, MI 48109, USA
4 Department of Astronomy, University of Massachusetts, LGRT-B 619E, 710 North Pleasant Street, Amherst, MA 01003-9305, USA
5 Purple Mountain Observatory, Chinese Academy of Sciences, 10 Yuanhua Road, Nanjing, Jiangsu 210093, People’s Republic of China
6 MPI für Radioastronomie, Auf dem Hügel 69, D-53121 Bonn, Germany
7 School of Astronomy and Space Science, Nanjing University, Nanjing 210023, People’s Republic of China
8 Key Laboratory of Modern Astronomy and Astrophysics, Nanjing University, Nanjing 210023, People’s Republic of China
9 31 Key Laboratory of Radio Astronomy, Chinese Academy of Sciences, Nanjing 210008, People’s Republic of China
10 Department of Astronomy, New Mexico State University, Las Cruces, NM 88003, USA
11 Department of Astronomy and Steward Observatory, University of Arizona, Tucson, AZ, USA

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Abstract

We report the discoveries of a nuclear ring of diameter 10″ (~1.5 kpc) and a potential low-luminosity active galactic nucleus (LLAGN) in the radio continuum emission map of the edge-on barred spiral galaxy NGC 5792. These discoveries are based on the Continuum Halos in Nearby Galaxies—an Expanded Very Large Array (VLA) Survey, as well as subsequent VLA observations of subarcsecond resolution. Using a mixture of Hα and 24 μm calibrations, we disentangle the thermal and nonthermal radio emission of the nuclear region and derive a star formation rate (SFR) of ~0.4 M☉ yr⁻¹. We find that the nuclear ring is dominated by nonthermal synchrotron emission. The synchrotron-based SFR is about three times the mixture-based SFR. This result indicates that the nuclear ring underwent more intense star-forming activity in the past, and now its star formation is in the low state. The subarcsecond VLA images resolve six individual knots on the nuclear ring. The equipartition magnetic field strength B_eq of the knots varies from 77 to 88 μG. The radio ring surrounds a point-like faint radio core of S_{GHz} = (16 ± 4) μJy with polarized lobes at the center of NGC 5792, which suggests an LLAGN with an Eddington ratio of ~10⁻⁵. This radio nuclear ring is reminiscent of the Central Molecular Zone of the Galaxy. Both of them consist of a nuclear ring and LLAGN.

Unified Astronomy Thesaurus concepts: Radio continuum emission (1340); Galaxy nuclei (609); Star formation (1569); Interstellar synchrotron emission (856)

1. Introduction

Edge-on galaxies are ideal laboratories for studying gas interchange between star-forming (SF) disks and the surrounding extraplanar and halo environment. Probing the properties of the medium located at the disk–halo interface allows us to study how the gas transfers into the disk, forms spiral arm, ring, and bar structures, and sustains the star-forming activity. The accumulation of inflowing gas in the nuclear region provides the necessary material for the activities of starbursts (SB) and active galactic nuclei (AGNs), and the environment of host galaxies is affected by the feedback of these activities. Therefore, the study of these feedback activities is essential to understanding the evolution of galaxies. Radio emission is free from extinction in the nuclear region, and high spatial (subarcsecond) resolution radio observations of nuclei are a useful way to understand how SB and AGN activities affect the evolution of host galaxies.

NGC 5792 is a nearby, highly inclined (i ≈ 70°–80°), barred spiral galaxy at a distance of about 31.7 Mpc (1″ ≈ 150 pc) in the constellation Libra (Baillard et al. 2011; Irwin et al. 2012a).

Previous optical studies indicate that NGC 5792 has an outer pseudo-ring of radius 31.5 kpc and an inner ring of radius 10.8 kpc (Comerón et al. 2014; see also Figure 1). Some basic parameters of NGC 5792 are listed in Table 1.

Recently, several authors have suggested that the nuclear rings of barred galaxies are regions of large gas surface densities and high star formation rates (SFRs; Bata & Combes 1996; Knappen 2005; Comerón et al. 2010). Nuclear rings are believed to form as a result of gas inflow toward the central region along dust lanes, where it stagnates near dynamical resonances. Due to the bar torque, the inflowing material, which loses most of its angular momentum, spirals in toward the ring region at the two “contact points” between the dust lanes and the ring, where the accumulated gas proceeds to move in nearly circular orbits and forms a luminous, compact ring around the galactic center (Athanassoula 1992; Heller & Shlosman 1994, 1996; Piner et al. 1995; Bata & Combes 1996; Regan et al. 1997; Benedect et al. 2002; Kim et al. 2012; Li et al. 2015; Ma et al. 2018). Typically located within the central kiloparsec, nuclear rings contain a mixture of neutral and ionized gas and dust with total masses of 10⁸–10¹⁰ M☉. (Heller & Shlosman 1996; Rubin et al. 1997). One of the most well-studied nuclear rings is the region of abundant molecular gas in our Milky Way galaxy, called the Central Molecular Zone (CMZ).
In this paper, we present the results of Continuum Halos in Nearby Galaxies—an EVLA Survey (CHANG-ES) observations (Irwin et al., 2012) for NGC 5792, and use our follow-up subarcsecond angular resolution VLA (6 and 9 GHz) observations, near-infrared (Hubble Space Telescope (HST) WFC3 F160W and F814W filters), and optical (Hα, HST/WFC3 F475W) images to investigate the central kiloparsec region of NGC 5792 in detail. We present an overview of the observations in Section 2. The information and morphological properties of our results are presented in Section 3. Our detailed analysis of the results is discussed in Section 4, with concluding remarks in Section 5.

2. Observations and Data Reductions

2.1. CHANG-ES Observations

NGC 5792 is one of the 35 highly inclined nearby galaxies in the CHANG-ES project. The CHANG-ES observations were carried out using the updated VLA during its commissioning period (2011–2012) at L-band (center frequency at 1.5 GHz in B, C, and D configurations) and C-band (center frequency at 6 GHz in the C and D configurations), in all polarization products. Details of the CHANG-ES observations for NGC 5792 are listed in Table 2.

2.2. High Spatial (Subarcsecond) Resolution VLA Observations

In addition to the CHANG-ES observations, we observed the nuclear region of NGC 5792 in three epochs (project ID: 15A-400; PI: Yang) with dual polarization with the VLA in A-configuration. These data were observed at C-band (centered at 6 GHz) and X-band (centered at 9 GHz). Our observations were centered at [R.A., decl.] (J2000) = [14°58′22.71″, −01°05′27.9″]. Corresponding observation logs are summarized in Table 2. We used the same flux calibrator and secondary calibrator as in the CHANG-ES observations.

Table 1

| NGC 5792 (PGC0053499) |
|------------------------|
| R.A. (J2000) | 14°58′22.71″ |
| Decl. (J2000) | −01°05′27.9″ |
| Distance (Mpc) | 31.7 (Irwin et al., 2012) |
| Inclination of disks (°) | 70°–80° (Baillard et al., 2011) |
| PA of major axis (°) | 84° (Barberà et al., 2004) |
| Classification | SBb |
| Nuclear Type | HII |
| SFR (M_L yr⁻¹) | 4.41 (Vargas et al., 2019) |
| M^e (M_L) | 10^7.78 (Misiriotis et al., 2004) |
| M^e (M_L) | 10^7.17 (Davis et al., 2014) |
| M^e (M_L) | 10^7.32 (Misiriotis et al., 2004) |
| Diameter of the outer pseudo-ring (kpc) | 413/63 (Comerón et al., 2014) |
| Diameter of the inner ring (kpc) | 146/22 (Comerón et al., 2014) |

Notes:
- The position angle (PA) is the angle between the line of nodes of the projected image and the north, measured toward the east.
- Star formation rate (SFR) in a 23.7 kpc diameter.
- The mass of the supermassive black hole.
- Stellar mass in a 72 kpc diameter.
- The total gas mass of this galaxy.
- The dust mass of this galaxy.

Our new Karl G. Jansky Very Large Array (VLA) A-configuration observations provide subarcsecond resolving power in the radio regime, allowing us to probe the nuclear region in NGC 5792. The goal of this paper is to provide an overview of the nuclear ring and to characterize its nature, on the basis of our high-resolution multiwavelength data, as well as to compare the nuclear ring with the CMZ in our Galaxy. Furthermore, we aim to probe the possible existence of an AGN at the center of NGC 5792.
2.3. Data Reductions

Each individual visibility data set was flagged, calibrated, imaged and restored using the Common Astronomy Software Applications package (CASA, version 4.5) following the standard procedures (more details can be found in Irwin et al. 2012b, Section 2.2). We inspected all visibility data by eye, and manually flagged bad data (due to radio frequency interference and instrumental effects). The Stokes I images were then produced using the CLEAN task, with the Multi-frequency Synthesis mode, nterms = 2, and the Briggs weighting with robust = 0. The CASA WIDEBANDPBCOR task was used to carry out wide-band primary beam corrections. Flux measurements were made from the primary beam corrected images. To estimate the radio spectral index between 6 and 9 GHz associated with each region, we smoothed the native resolution of the 6 and 9 GHz images to a common circular beam (FWHM = 0\,"/3) for consistent measurements of flux densities across the two frequencies. All flux densities (listed in Col. 5 and Col. 6 of Table 3) are measured by using the IMSTAT task in the corresponding region, whose the position and radius are listed in Col. 2 and Col. 3 of Table 3, and we state how to define the corresponding regions in Section 3.1. The rms error was measured in a signal-free portion (near source) of each image. The uncertainty of the flux densities for each region was derived via the equation

$$\sigma = \sqrt{N_b \times \text{rms}^2 + (\eta \times S)^2},$$

in which $N_b$ corresponds to the number of synthesized beams, and $\eta$ is a factor that accounts for uncertainties in the calibration system, for which we adopted $\eta = 0.03$ for the VLA radio images (Perley & Butler 2013); $S$ is the flux density of the corresponding region. Only the flux density of the core was measured by fitting a Gaussian to the corresponding region in the 6 GHz A-array image with the IMFIT task, and its fitting region was approximately two times the FWHM of the synthesized beams. To maximize the signal-to-noise ratio, we used the CONCAT task to combine the two-epoch visibility data sets (at X-band in A-configuration) into a concatenated visibility data set.

Stokes $Q$ and $U$ maps (only in CHANG-ES observations) were formed with the same sets of input parameters as the total intensity images. We derived the linearly polarized intensity image as the top plane in Figure 2 by the relation of

$$P = \sqrt{Q^2 + U^2 - \sigma_{Q,U}^2},$$

where $\sigma_{Q,U}$ is the rms noise in the $Q$ and $U$ maps. The polarization angle of the observed electric vector $(\chi)$ is given by $\chi = 1/2 \arctan(U/Q)$; and the

| Frequency Array | 1.5 GHz (L-band) | 6.0 GHz (C-band) | 9 GHz (X-band) |
|-----------------|-----------------|-----------------|----------------|
| Date of observations | 2011 Dec 30 | 2012 Feb 4 | 2015 Jul 28 | 2015 Jul 9 |
| Total bandwidth (MHz) | 512 | 2042 | 6.0 | 2.7 |
| Obs. time (hr$^f$) | 7 | 6.0 | 4.5 | 2.3 |
| Flux calibrator$^d$ | 3C 286 | 3C 286 | 3C 286 | 3C 286 |
| Phase calibrator$^d$ | J1505+0326 | J1505+0326 | J1505+0326 | J1505+0326 |
| Pol. leakage calibrator$^d$ | J1331+3030 | J1331+3030 | J1331+3030 | ... |
| $uv$ weighting$^g$ | Briggs | Briggs | Briggs | Briggs |
| Notes. | | | | |

$^a$ Project ID: 10C-119.
$^b$ Project ID: 15A-400.
$^c$ Total observing time before flagging.
$^d$ This source was also used as the bandpass calibrator and for determining the absolute position angle for polarization.
$^e$ This source is a “primary” calibrator in the sense of its amplitude errors ($\leq 3\%$) and phase errors ($\leq 2.5\%$) in all arrays and in both bands.
$^f$ This zero-polarization calibrator was used to determine the polarization leakage terms.
$^g$ Robust = 0 was used in each case, as employed in the CASA clean task.
$^h$ Scales used for the multiscale clean.
$^i$ Synthesized beam FWHM of major and minor axis, and position angle.
$^j$ The rms error was measured manually on each image in an emission-free region.
$^k$ Flux densities of the total intensity emission in the nuclear region (nuclear ring and core).
Table 3
Flux Densities and Spectral Indices in the Nuclear Region of NGC 5792

| Region | Center (J2000) | Radius (arcseconds) | Radius (kpc) | S_{α,6 GHz} (mJy) | S_{α,9 GHz} (mJy) | S_{α,6 GHz} (S × α^{0.7}) | S_{α,9 GHz} (S × α^{0.7}) | Total α | Nonthermal α_{NT} |
|--------|----------------|---------------------|--------------|------------------|-----------------|------------------|------------------|--------|-----------------|
| A      | 224°5960102, -1°091173824 | 1.25 ± 0.70 | 0.18 ± 0.11 | 0.813 ± 0.033 | 0.296 ± 0.039 | -2.49 ± 0.34 | -2.58 ± 0.37 |        |                 |
| B      | 224°5931713, -1°09131474 | 1.33 ± 1.05 | 0.20 ± 0.16 | 1.337 ± 0.048 | 0.685 ± 0.050 | -1.65 ± 0.20 | -1.83 ± 0.30 |        |                 |
| C      | 224°5944998, -1°090852332 | 0.33 | 0.05 | 0.105 ± 0.008 | 0.057 ± 0.013 | -1.49 ± 0.59 | -1.58 ± 0.64 |        |                 |
| D      | 224°5942301, -1°090858643 | 0.35 | 0.05 | 0.095 ± 0.008 | 0.027 ± 0.014 | -3.06 ± 1.24 | -4.25 ± 2.50 |        |                 |
| E      | 224°5947158, -1°090765536 | 0.28 | 0.04 | 0.069 ± 0.007 | 0.021 ± 0.011 | -2.97 ± 1.32 | -3.61 ± 1.93 |        |                 |
| F      | 224°5943819, -1°091571492 | 0.29 | 0.04 | 0.051 ± 0.007 | 0.028 ± 0.011 | -1.43 ± 1.04 | -1.50 ± 1.11 |        |                 |
| N      | 224°5945961, -1°091194587 | 3.80 ± 0.95 | 0.57 ± 0.14 | 0.619 ± 0.046 | 0.042 ± 0.074 | ... | ... |        |                 |
| T      | 224°5945961, -1°091183738 | 7.10 ± 1.80 | 1.07 ± 0.27 | 5.258 ± 0.177 | 1.592 ± 0.147 | -2.95 ± 0.24 | -3.87 ± 0.80 |        |                 |
| R      | 224°5945961, -1°091183878 | T - N | T - N | 4.639 ± 0.155 | 1.550 ± 0.127 | -2.70 ± 0.22 | -3.34 ± 0.58 |        |                 |
| core   | 224°5945418, -1°091206343 | <0.20 | <0.03 | 0.016 ± 0.004 | <0.021 | <0.66 | <0.74 |        |                 |

Note. Regions N and T are ellipses with PA ∼ 84° of the major axis. Region R is the ring defined by subtracting region N from the total region T. S_{6 GHz} and S_{9 GHz} are the flux densities of the regions (we convolved the C-band and X-band images to the same beam size; 0''3 × 0''3). The core is the magenta cross in the center of NGC 5792. The spectral indices in Column 8 are obtained from the separated nonthermal emission (see Section 3.3 for details).

3. Results

3.1. The Morphology of the Radio Emission

The 1.5 and 6 GHz total intensity images in different scales are shown in Figure 3, in which the panels (a)–(f) are arranged according to their fields of view (FOVs) as well as by descending frequency and Figures 3(a), (b), and (c) are of the same FOV. Two arm-like structures extending from the nuclear region to a radius of 90'' (∼14 kpc) are discernible in the 6 GHz D-configuration and 1.5 GHz C-configuration maps (Figures 3(a) and (b), respectively). The two radio arm-like structures partially overlap the optical inner ring (the cyan ellipse in Figure 1). The extended 1.5 GHz emission, as revealed in the D-configuration image (Figure 3(c)), appears to have a slight extension along the minor axis of the disk.

Besides that, in the 1.5 GHz B-configuration map (Figure 3(e)), we detected a loop to the north of the nucleus with a signal-to-noise ratio of ∼3, as well as two emission peaks in the nuclear region. Those two peaks are also visible in the 6 GHz C-configuration map (Figure 3(d)), and are further resolved as a nuclear radio ring of diameter 1.5 kpc, with several knots spread over the ring, in the 6 (C-band) and 9 GHz (X-band) A-configuration maps (Figures 4(a) and (b)).

We consider the regions within the 3σ contours to be from the real signals, and the 3σ contours at 9 GHz are just enclosed in the 6σ contours at 6 GHz. Therefore, we define the knot regions where the intensity is 6 and 3 times above the rms noise at 6 and 9 GHz, respectively. The outermost cyan and magenta contours in Figure 4(a) represent the 6σ level at 6 GHz and 3σ level at 9 GHz, respectively. These knot regions are labeled as A, B, C, D, E, and F. The coordinates and sizes of the knots A to F are listed in Table 3.

We also define the ellipse that just encloses these knots as the total nuclear region T and the inside ellipse just detached from these knots as region N. Region R is designated by subtracting region N from the total nuclear region T. The observed axis ratio of the nuclear ring, as measured in radio continuum, is 3.75, which implies an inclination i ∼ 74° ± 2°. This is consistent with the inclination (70°–80°) of NGC 5792. In the center of the radio nuclear ring, we have detected a compact core with a flux density of 16 ± 4 μJy (∼4σ) at 6 GHz.

12 https://library.nrao.edu/public/memos/evla/evlam_195.pdf
13 Falcke et al. (1998) reported the pointing accuracy of both HST and the VLA is 0''5–2''. However, owing to the lack of common sources, it is virtually impossible to match the optical/radio astrometry to better than the individual pointing accuracy.
3.2. Spectral Index of the Nuclear Ring

We made a band-to-band spectral index map from the 1.5 GHz B-configuration map to the 6 GHz C-configuration map of similar resolution (7″5 × 6″7). The spectral index (S ∝ ν^α) map was created using a cutoff at 3σ of the intensity maps (see Irwin et al. 2019, Section 3.4 for more details). As shown in Figure 2, the mean spectral index of the nuclear region is ∼−0.7 with a standard deviation of 0.15, while the mean spectral index of the north and south arms are ∼−0.4 with a standard deviation of 0.2 and ∼−0.3 with the standard deviation of 0.2. By setting the multifield parameter niter = 2, we also checked the mean in-band spectral index of the nuclear region, which is consistent with the band-to-band one.

In order to assess the spectral index in the nuclear ring, we used the higher-resolution (∼0″3) 6 and 9 GHz observations to derive the total spectral index α for each defined region in Figures 4(a) and (b). The intensity maps of those two frequencies are convolved to a restoring beam of the same size (FWHM = 0″3) for consistency. The photometric information is summarized in Cols. 5 and 6 in Table 3, and the derived total spectral index α is presented in Col. 7 of the same table. The α of the separate knots covers a range of −1 to −3, and that of the nuclear region as a whole is as low as ∼−2.95 ± 0.24. The α6–9 GHz ∼ −2.95 ± 0.24 is steeper than the α1.5–6 GHz ∼ −0.70 ± 0.15 found by Li et al. (2016). Among the six knots, knot D has the steepest spectrum of α ∼ −3.06 ± 1.24, while knot F has the flattest spectrum of α ∼ −1.43 ± 1.04. We also checked the in-band spectral index with the A-array data, but only got a meaningful value for knot B at 6 GHz: −0.98 ± 0.21. This value is larger than the band-to-band spectral index (−1.65; see Table 3). We note that regions N and T are larger than the largest angular scale (LAS), which may suffer from losing the 9 GHz flux density; meanwhile, for the small knots whose flux density is as low as three times the rms value, corresponding region sizes are close to the synthesized beam of the 9 GHz image and may lose diffuse emission. As a consequence, we may have derived steeper spectra. To assess the influence of the potential missing 9 GHz flux, we used the observed 6 GHz flux density, adopted α1.5–6 GHz ∼ −0.70 to the 6–9 GHz range, and estimated the extrapolated S9 GHz,ext values in those regions. We found that those S9 GHz,ext values are about 1.3–2.5 times the corresponding observed S9 GHz,obs. Further physical discussion on the steep spectrum will be given in Section 4.1.

We also detected a point-like source (marked as the core) at the center of NGC 5792 in the 6 GHz image (Figure 3(f)), with a flux ∼ 4σ above the average background level, but failed to detect it in the 9 GHz map. We used its 3σ upper limit to estimate the upper limit of the total spectral index of the core, and found a value of ≤0.66. The nonthermal αNT of the core is

![Figure 2. Top: polarization (P) contours and magnetic field (B) vectors overlaid on an optical SDSS r-band image. The contours are at 16.2 (3σ), 22, 30, 50, and 70 µJy beam⁻¹, where the beam size is shown in the lower left and has dimensions of 16″1 × 15″5, −87″4. The B vectors have been cut off at 5σ. The radio data are at 6 GHz and were observed with the VLA in D-configuration with a 6 kλ taper applied during imaging. Bottom: the spectral index distribution between the 6 GHz C-configuration data and 1.5 GHz B-configuration data. The angular resolution (blue ellipse) is 7″5 × 6″7. Total intensity contour levels (1.5 GHz in B-configuration) are shown at an rms of 20 μJy beam⁻¹.]
The 6 GHz C-configuration image with contours at an rms of 0.018 mJy beam$^{-1}$ × [10, 100]. The 1.5 GHz C-configuration image with contours at an rms of 0.03 mJy beam$^{-1}$ × [10, 100], the 1.5 GHz D-configuration image with cyan contours at an rms of 0.045 mJy beam$^{-1}$ × [10, 100]; the blue contours show the corresponding contour from (e), and the magenta contours show the corresponding contour from (f), and the magenta cross indicates the position of the core.

Figure 3. Total radio intensity images with contours. The regions in (a), (b), and (c) have the same scale. The red dashed box shown in these three planes is blown up in (d), indicated by the arrows. The regions in (d) and (e) are of the same scale. The blue dashed box shown in these two planes is blown up to (f), indicated by the arrows. (a) The 6 GHz D-configuration image with contours at an rms of 0.018 mJy beam$^{-1}$ × [10, 100]. (b) The 1.5 GHz C-configuration image with contours at an rms of 0.03 mJy beam$^{-1}$ × [10, 100]. (c) The 1.5 GHz D-configuration image with cyan contours at an rms of 0.045 mJy beam$^{-1}$ × [10, 100]; the blue contours show the corresponding contour from (b), yellow contours show the corresponding contour from (e), and the magenta contours show the corresponding contour from (f). (d) The 6 GHz C-configuration image with contours at an rms of 0.018 mJy beam$^{-1}$ × [10, 100, 225]. (e) The 1.5 GHz B-configuration image with contours at an rms of 0.02 mJy beam$^{-1}$ × [3, 100, 225]. (f) The 6 GHz A-configuration image with contours at an rms of 4 mJy beam$^{-1}$ × [3, 7]. The resolution (beam size) is indicated in the bottom left corner of each panel. The magenta cross indicates the position of the core.

<0.75 after excluding the thermal contribution with the method described in Section 3.3.

3.3. Thermal (Free–Free) versus Nonthermal (Synchrotron) Radio Emission

The total observed radio emission is a combination of thermal free–free emission and nonthermal synchrotron emission, which have different origins (Condon 1992): massive stars and their associated H II regions would be responsible for the thermal free–free emission, while supernovae (SNe), supernova remnants (SNRs), and AGNs would account for the nonthermal synchrotron emission (Clemens et al. 2008; Barcos-Muñoz et al. 2017). It is necessary to separate these two kinds of emissions in order to probe their origins and the processes behind them.

We estimated the thermal (free–free) radio emission contribution from extinction-corrected H$\alpha$ measurements. When galaxies are edge-on or very dusty, Vargas et al. (2019) claimed that the thermal radio component is best estimated using the mixture method as a mixture of H$\alpha$ and 24 $\mu$m calibration. The H$\alpha$ and 24 $\mu$m calibration is from Calzetti et al. (2007) and Vargas et al. (2019):

$$F_{\text{H}\alpha, \text{corr}} = F_{\text{H}\alpha, \text{obs}} + a \cdot F_{24 \mu m}. \quad (1)$$

We adopted a value of $a = 0.042$; there is a linear relationship between 22 $\mu$m flux and 24 $\mu$m flux ($F_{24 \mu m} = 1.03F_{22 \mu m}$ from Wiegert et al. 2015). We used the WISE 22 $\mu$m flux ($F_{22 \mu m} = (1.71 \pm 0.03) \times 10^{-11}$ erg s$^{-1}$ cm$^{-2}$) within an elliptical nuclear region of radius 7.5$' \times 4.8$ from Jarrett et al. (2013) and the observed H$\alpha$ flux $F_{\text{H}\alpha, \text{obs}} = (3.5 \pm 0.7) \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ in the same region to derive $F_{\text{H}\alpha, \text{corr}} = (1.1 \pm 0.3) \times 10^{-12}$ erg s$^{-1}$ cm$^{-2}$; thus, we estimated the average extinction of $A_{\text{H}\alpha} = 1.3 \pm 0.4$ within this region. The spatial resolution of the WISE 22 $\mu$m image prevents us from assessing the extinction-corrected H$\alpha$ flux of these regions, which are smaller than the nuclear region of radius 7.5$' \times 4.8$. Region T is close to this limit, so we used the average $A_{\text{H}\alpha} = 1.3 \pm 0.4$ in region T. Calzetti et al. (2007) also claimed an uncertainty of 20% for the coefficient $a$, which we also accounted for to evaluate the uncertainty of $F_{\text{H}\alpha, \text{corr}}$. Therefore, the thermal radio emission in the region T could be derived from the extinction-corrected H$\alpha$ flux (Condon 1992).
We assumed the electron temperature to be $T_e = 10^4$ K; then, the derived thermal free–free radio flux densities are $0.66$ mJy and $0.64$ mJy at 6 GHz and 9 GHz, respectively, and those values are $\sim 13\%$ of the total radio emission in region T of NGC 5792 at 6 GHz and 40\% at 9 GHz.

We also probed the thermal radio emission of the separate knots on the nuclear ring. However, the spatial resolution of the optical and infrared observations prevented us from assessing the extinction-corrected H$\alpha$ flux of each knot. Instead, we employed the average extinction coefficient of $A_{H\alpha} = 1.3 \pm 0.4$ in the $7''5 \times 4''8$ radius region to correct the extinction of all of the knots in the region T, and we list the extinction-corrected $F_{H\alpha,corr}$ in Col. 3 of Table 4. We note that $F_{H\alpha,corr}$ of the six knots A–F potentially were estimated with uncertainties due to different levels of extinction throughout the nuclear rings. As shown in the HST image (Figure 4(d)), the knots A, B, F, and C are apparently more obscured by dust, indicating that $F_{H\alpha,corr}$ of these knots may be underestimated.

Finally, the thermal radio emission of the separate knots in region T are assessed by Equation (2). We list the thermal radio emission of the knots in Col. 4 (at 6 GHz) and Col. 6 (at 9 GHz) of Table 4. The fractions of thermal emission to total radio emission are listed in Col.5 (at 6 GHz) and Col.7 (at 9 GHz). All of the above uncertainties are accounted for using error-propagation techniques.

Furthermore, we probed the variation of $A_{H\alpha}$ inside the nuclear region with the high spatial resolution HST F814W and F475W images by comparing the observed flux ratio of those two bands to the intrinsic one. The latter one was assessed as 2.9 by modeling the continuous star formation case of a constant SFR by means of the stellar synthesis model STARBURST99 (Leitherer et al. 1999). We found that $A_{H\alpha}$ of knots A to F varies from 2.0 to 3.6 with lowest values of 2.0 and 2.4 at knot D and E, respectively, and grows as high as 3.6 at knot A. This variation is consistent with what we saw in the multicolor HST image (Figure 4(d)), which exhibits a dust lane at the southeast portion. However, the absolute value of $A_{H\alpha}$ relies on the comprehensive investigation of the stellar population inside the nuclear ring, which is beyond the scope of this paper.
The main goal of this section is to determine the most important parameter, SFR. Using Equation (2) in Murphy et al. (2011) with the extinction-corrected Hα emission, we estimated the SFRs of A, B, C, D, E, F, N, R, T, and the core (marked in Figure 4; region R is the ring defined by subtracting the region N from region T, and the core is the point-like source in the center of NGC 5792) as follows:

\[
\frac{\text{SFR}}{M_\odot \text{yr}^{-1}} = 5.37 \times 10^{-42} \left( \frac{L_{\text{H}\alpha, \text{corr}}}{\text{erg s}^{-1}} \right).
\]

The results are listed in Col. 8 of Table 4. We assessed the SFR in the nuclear region (region R) for NGC 5792 to be ~0.32 $M_\odot$ yr$^{-1}$; however, the SFR of the total nuclear region (region T, in a ~1.5 kpc diameter) is ~0.42 $M_\odot$ yr$^{-1}$. It appears that the majority of the star formation activity is taking place on the ring in the nuclear region. According to Vargas et al. (2019), the SFR of NGC 5792 in a ~23.7 kpc diameter is 4.41 $M_\odot$ yr$^{-1}$, which was estimated using a combination of the Hα and 22 μm luminosity. We also estimated the SFR surface density (SFR$_{\text{SD}}$) by dividing the areas of the regions. The SFR$_{\text{SD}}$ in the nuclear region T is 0.46 $M_\odot$ yr$^{-1}$ kpc$^{-2}$, and the other SFR$_{\text{SD}}$ values are listed in Col. 9 of Table 4.

4. Discussion

4.1. The Origin of Nonthermal Radio Emission in the Nuclear Ring

We show a nuclear ring with a radius of 5′′ (750 pc) in high-resolution 6 and 9 GHz images of NGC 5792 observed with the VLA. The ring emission dominates the total radio emission in the nuclear region, and its size and orientation in the radio regime is consistent with that in the optical and near-infrared bands, as shown in Figure 4. Based on the high-resolution data at 6 GHz, we found that the nuclear ring is dominated by nonthermal synchrotron emission. The thermal radio continuum emission associated with the star-forming process accounts for only ~11% of the observed total radio continuum emission. The polarization contour also indicates the existence of nonthermal synchrotron radio emission in the nuclear region, as shown in the top panel of Figure 2.

Possible origins of the nonthermal emission include SNe and SNRs related to the star-forming process and contributions of AGN activity. In the case of SNRs as the dominant accelerators of CREs, the excess nonthermal emission should originate from the deaths of massive stars in supernova explosions. Therefore, the nonthermal radio continuum emission traces the star-forming process that occurred roughly an average massive star main-sequence lifetime ago (~10 Myr; Leitherer et al. 1999), rather than the instantaneous one. Using Equation (14) of Murphy et al. (2011), we derived a synchrotron-based SFR of 1.2 $M_\odot$ yr$^{-1}$ with the nonthermal synchrotron flux of 4.1 mJy at 6 GHz and $\alpha_{6\text{GHz}} = -0.7$. This value is roughly three times that of the instantaneous SFR of 0.32 $M_\odot$ yr$^{-1}$ inferred by using a combination of the Hα and 24 μm emission. This result indicates that the nuclear ring in NGC 5792 underwent a more intense star-forming activity in the past, and now the star formation in the nuclear region is in a low state. Some numerical simulations found that the ring SFR is closely related to the mass inflow rate (e.g., Seo et al. 2019). The instantaneous ring SFR may reflect a decrease in the mass inflow rate. However, in the nuclear region, the contribution of the AGN to the nonthermal emission cannot be fully ruled out. The existence of an AGN will be discussed in Section 4.4.

Comparing with $\alpha_{6\text{GHz}} = -0.70 \pm 0.15$ (Li et al. 2016), we measured a steeper $\alpha_{6\text{GHz}} = -2.95 \pm 0.24$ for the nuclear region. In addition to the potentially lost flux density due to the limitation of the LAS, as well as the synthesized beam at 9 GHz, the CREs lose energy by synchrotron, inverse Compton, and escape losses can also change the nonthermal spectral index at different frequencies and regions (Beck 2007). Especially, the magnetic field is complex and includes the contribution of an AGN in the nuclear region. For example, in the case of NGC 6946’s ordered magnetic field, the CREs suffer stronger synchrotron losses, and hence there is a rather steep spectrum (Tabatabaei et al. 2013). The polarized intensity...
found in the nuclear region of NGC 5792 is another piece of evidence of this CRE losing energy scenario.

4.2. Equipartition Magnetic Field Strengths

Our results suggest that the nuclear region is dominated by nonthermal synchrotron emission. Another factor determining the intensity of the nonthermal emission is the magnetic field. Therefore, we estimated the magnetic field from the 6 GHz nonthermal flux density. We assumed the equipartition between the energy densities of the total cosmic rays (dominated by protons) and the total magnetic field. We used the revised formula given by Beck & Krause (2005) to calculate the equipartition magnetic fields $B_{\text{eq}}$. We also assumed the ratio of the relativistic proton number density to that of the electrons is 100 and adopted a spectral index of $-0.7$; the path lengths through the emitting medium along the line of sight are taken to be the same as the maximal widths of the regions in the sky plane. The derived $B_{\text{eq}}$ in each region is listed in Col. 10 of Table 4. The range of $B_{\text{eq}}$ in the nuclear ring is from 77 to 88 $\mu$G and has a mean of 84 $\mu$G. In the core region of NGC 5792, $B_{\text{eq}}$ goes up to 113 $\mu$G.

There is a similar nuclear ring in NGC 1097, whose radio emission is also dominated by nonthermal emission. The equipartition magnetic field strengths in the ring change between 50 and 80 $\mu$G (Beck et al. 2005). The mean $B_{\text{eq}}$ of the NGC 5792 nuclear ring is about 50% higher than the mean value of $\sim 55$ $\mu$G in NGC 1097 (Beck et al. 2005). Tabatabaei et al. (2018) claimed that strong magnetic fields limit the efficiency of massive star formation while fostering enhanced low-mass star formation. Therefore, the nuclear region of N5792 may be undergoing massive star formation quenching.

4.3. Star Formation on the Nuclear Ring

The separation of knots on the nuclear ring of NGC 5792 indicates that star formation is or was concentrated in discrete regions. How do these knots (concentrated star-forming regions) form on the ring? Böker et al. (2008) proposed two models of star formation: the “popcorn” and “pears on a string” models. In the former one, star formation occurs in dense clumps that are randomly distributed along a nuclear ring. This type of star formation, presumably caused by the gravitational instability of the ring itself (Elmegreen 1994), does not produce a systematic gradient in the ages of young star clusters along the azimuthal direction (see also Benedict et al. 2002). In the latter one, star formation takes place preferentially at the contact points between a ring and the dust lanes. This may happen because the gas clouds with the largest densities are usually placed at the contact points due to orbit crowding (Kenney et al. 1992; Reynaud & Downes 1997; Kohno et al. 1999; Hsieh et al. 2011). Since star clusters age as they orbit along the ring, this model consequently predicts a bipolar azimuthal age gradient of star clusters starting from the contact points (see also Ryder et al. 2001; Allard et al. 2006; Böker et al. 2008; Mazzuca et al. 2008; van der Laan et al. 2013). Mazzuca et al. (2008) found that $\sim 50\%$ of the nuclear rings in their sample galaxies show azimuthal age gradients and that such galaxies have, on average, a larger value of the mean SFR than those without noticeable age gradients.

Observational evidence indicates that the SFR in the nuclear rings of normal barred galaxies spans a wide range $\sim 0.1$–$10$ $M_\odot$ yr$^{-1}$ (Mazzuca et al. 2008; Ma et al. 2018). That of NGC 5792, $\sim 0.4$ $M_\odot$ yr$^{-1}$, is at a low level. The SFR in the nuclear ring is affected by many factors, for example, the strength of nonaxisymmetric perturbations in galaxies, the inflow rate of the gas, and the magnetic field strength. The observations in Ma et al. (2018) support the observation that strongly barred galaxies tend to have low SFRs in their rings (see also Mazzuca et al. 2008; Comerón et al. 2010). Besides that, numerical simulations (Seo & Kim 2013; Seo et al. 2019) show that the SFR is closely related to the mass inflow rate to the ring rather than the ring mass. For a range of inflow rate 0.125–$8 M_\odot$ yr$^{-1}$, the SFR is about 80% of the inflow rate (Moon et al. 2021). The discovery by Tabatabaei et al. (2018) shows that the strong magnetic field can decelerate massive star formation and can help the formation of low-mass stars. Further radio observations are needed to address which one is the dominant factor.

4.4. Is There an AGN in the Center?

We found a potential AGN radio counterpart in the 6 GHz A-configuration map (see Figure 3(d)), with a flux density of $16 \pm 4 \mu$Jy. We fitted the radio core with a Gaussian, and after deconvolving from the synthesized beam we found that the size of the core is less than the FWHM of the synthesized beam in both the major and minor axis directions. In other words, the point-like radio core is unresolved in the A-configuration map, which has a resolution of $\sim 0''3$. This point-like feature is one of the criteria for determining the presence of an AGN (Irwin et al. 2019). However, the origin of other kinds of emission components, e.g., SNRs, cannot be ruled out completely.

It is well known that AGNs can have very flat spectra, because AGNs are compact and show self-absorbed synchrotron spectra (Markoff 2010). The core region of NGC 5792 shows a nonthermal spectral index $\alpha_{\text{NT}}$, $\leq 0.74$ between 6 and 9 GHz. That said, given that the $\alpha_{6,9}$ GHz of the nuclear region is $\sim -0.7$ and the flux density of the core is $16 \mu$Jy at 6 GHz, we estimated that the flux density of the core is $\sim 12 \mu$Jy at 9 GHz. This value is too weak to be detected at 9 GHz.

Figure 2 shows the linear polarization image from the CHANG-ES D-configuration, 6 GHz observations, along with the polarization vectors superimposed. The image reveals two apparent radio lobes on kiloparsec scales, bolstering the AGN hypothesis. We stress that the image has not been corrected for Faraday rotation, and an attempt at reconstructing the image using rotation measure synthesis did not reveal these lobes, possibly because of their faintness. Nevertheless, the polarized intensity does appear to show evidence of past nuclear activity, similar to what has been found in NGC 2992 (Irwin et al. 2017).

Additionally, the optical HST image (see Figure 4(d)) suggests that the core seems to be obscured by dust in the center of NGC 5792. Based on these clues of the point-like feature, the polarized lobes, and the feature of the optical image, we suggest that a potential AGN is at the center of NGC 5792.

The radio luminosity of the core of NGC 5792 is $\sim 2.0 \times 10^{25}$ erg s$^{-1}$ Hz$^{-1}$ at 6 GHz. The nucleus of NGC 5792 was detected as an X-ray source (4XMM J145822.6-010525 in the XMM-Newton Serendipitous Source Catalog14) with $L_{0.2–12 \text{ keV}} \sim 2.4–20 \times 10^{39}$ erg s$^{-1}$. Davis

14 https://heasarc.gsfc.nasa.gov/W3Browse/xmm-newton/xmmssc.html
et al. (2014) estimated the mass of the black hole in NGC 5792 as $M_\bullet \sim 10^{7.17} M_\odot$. Thus, the bolometric luminosity of the core is estimated to be $\sim 10^{-5} L_{\text{Edd}}$. The radio core of NGC 5792 can thus be interpreted as a low-luminosity AGN (LLAGN).

4.5. Comparison with the Center of Our Galaxy

The nuclear region of NGC 5792 is reminiscent of the CMZ in our Galaxy. Both of them contain a nuclear ring and an LLAGN. A pair of contact point knots A and B on the nuclear ring of NGC 5792, located opposite each other, are similar to the distribution of the two brightest massive clumps Sgr B2 and Sgr C on the CMZ (see Figure 21 in Bally et al. 2010). However, the NGC 5792 nuclear ring is three times larger in size compared to the CMZ, which has a diameter of $\sim 400$ pc (Morris & Serabyn 1996; Yusef-Zadeh et al. 2009). By contrast, the stellar mass of NGC 5792 out to a diameter of 72 kpc is $10^{10.9}$ (Sorai et al. 2019), which is comparable to the stellar mass of $\sim 10^{11} M_\odot$ of our Galaxy within a diameter 30 kpc (Mezger et al. 1996).

The numerical simulation by Seo et al. (2019) showed that the ring SFR is closely related to the mass inflow rate onto the ring, and suggested that the low current SFR of the CMZ is due to a low mass inflow rate in the near past. The SFR of the CMZ is at a level of 0.08–0.15 $M_\odot$ yr$^{-1}$ (Yusef-Zadeh et al. 2009). The star formation of the nuclear ring in NGC 5792 is also in a low state (Yusef-Zadeh et al. 2009), which indicates the low mass inflow rates; however, there are not yet observations to probe this speculation. Further observations of molecular gas around the nuclear region in NGC 5792 will help to confirm this speculation.

5. Summary

Based on the subarcsecond angular resolution radio (at 6 and 9 GHz), near-infrared (HST/WFC3 F160W, F814W), and optical (Hα, HST/WFC3 F475W) observations, we investigated the nuclear region of NGC 5792. The study can be summarized as follows:

1. We detected a well-defined nuclear ring at 6 and 9 GHz based on the VLA A-configuration observations. The ring can also be partially recognized in the HST and APO Hα images, which suffer significant dust obscuration.

2. We used the 24 $\mu$m emission to calibrate the dust extinction of the Hα emission in the nuclear region, then used the extinction-corrected Hα emission to separate thermal and nonthermal emission. We found that the nuclear ring is dominated by the nonthermal synchrotron emission. The excess nonthermal emission may be related to the past star-forming process.

3. Using the extinction-corrected Hα emission, we also estimated the SFRs of regions A, B, C, D, E, F, R, T, and the core. The SFR in the nuclear region, $\sim 0.4 M_\odot$ yr$^{-1}$, is at a low level among the range that the SFRs in the nuclear rings of normal barred galaxies spans. Further radio observations are needed to pin down its dominant cause. We also determined that the equipartition magnetic field strength $B_{\text{eq}}$ of the knots change between 77 and 88 $\mu$G with the synchrotron emission at 6 GHz. The strong magnetic field may prevent the collapse of gas to form massive stars.

4. We found that the nuclear radio ring surrounds a faint and compact ($r \sim 50$ pc) radio core at the center of NGC 5792 in the 6 GHz image, with a flux density of $16 \pm 4$ $\mu$Jy and polarized lobes, suggesting that the central source is a putative AGN.

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ORCID iDs

Yang Yang (杨阳) https://orcid.org/0000-0001-7254-219X
Judith Irwin https://orcid.org/0000-0002-2046-6727
Jiangtao Li https://orcid.org/0000-0001-6239-3821
Theresa Wiegent https://orcid.org/0000-0002-3502-4833
Q. Daniel Wang https://orcid.org/0000-0002-9279-4041
Wei Sun https://orcid.org/0000-0002-5456-0447
A. Damas-Segovia https://orcid.org/0000-0002-5747-8510
Zhiyuan Li https://orcid.org/0000-0003-0355-6437
Zhiqiang Shen https://orcid.org/0000-0003-3540-8746
René A. M. Walterbos https://orcid.org/0000-0002-0782-3064
Carlos J. Vargas https://orcid.org/0000-0001-7936-0831

References

Allard, E. L., Knapen, J. H., Peletier, R. F., et al. 2006, MNRAS, 371, 1087
Athanassoula, E. 1992, MNRAS, 259, 345
Baillart, A., Bertin, E., de Lapparent, V., et al. 2011, A&A, 532, A74
Bally, J., Aguirre, J., Battersby, C., et al. 2010, ApJ, 721, 137
Barberá, C., Athanassoula, E., & García-Gómez, C. 2004, A&A, 415, 849
Barcos-Muñoz, L., Leroy, A. K., Evans, A. S., et al. 2017, ApJ, 843, 117
Beck, R., 2007, A&A, 470, 539
Beck, R., Fletcher, A., Shukurov, A., et al. 2005, A&A, 444, 739
Beck, R., & Krause, M. 2005, AN, 326, 414
Benedict, G. F., Howell, D. A., Jorgensen, I., et al. 2002, AJ, 123, 1411
Böker, T., Falcón-Barroso, J., Schinnerer, E., et al. 2008, AJ, 135, 479
Buta, R., & Combes, F. 1996, FCPH, 17, 95
Calzetti, D., Kennicutt, R. C., Engelbracht, C. W., et al. 2007, ApJ, 666, 870
Clemens, M. S., Vega, O., Bressan, A., et al. 2008, A&A, 477, 95
Comerón, S., Knapen, J. H., Beckman, J. E., et al. 2010, MNRAS, 402, 2462
Comerón, S., Salo, H., Laurikainen, E., et al. 2014, A&A, 562, A121
Condon, J. J. 1992, ARA&A, 30, 575
Davis, B. L., Berrier, J. C., Johns, L., et al. 2014, ApJ, 789, 124
Elmegreen, B. G. 1994, ApJL, 425, L73
Falcke, H., Wilson, A. S., & Simpson, C. 1998, ApJ, 502, 199
Heller, C. H., & Shlosman, I. 1994, ApJ, 424, 84
Heller, C. H., & Shlosman, I. 1996, ApJ, 471, 143
Hsieh, P.-Y., Matsushita, S., Liu, G., et al. 2011, ApJ, 736, 129
Irwin, J., Beck, R., Benjamin, R. A., et al. 2012a, AJ, 144, 43
Irwin, J., Beck, R., Benjamin, R. A., et al. 2012b, AJ, 144, 44
Irwin, J., Wiegent, T., Merritt, A., et al. 2019, AJ, 158, 21
Irwin, J. A., Schmidt, P., Damas-Segovia, A., et al. 2017, MNRAS, 464, 1333
Jarrett, T. H., Masci, F., Tsai, C. W., et al. 2013, AJ, 145, 6
Kennedy, J. D. P., Wilson, C. D., Scoville, N. Z., et al. 1992, A&JL, 395, L79
Kim, W.-T., Seo, W.-Y., Stone, J. M., et al. 2012, ApJ, 747, 60
Knapen, J. H. 2005, A&A, 429, 141
Kohno, K., Kawabe, R., & Vila-Vilaró, B. 1999, ApJ, 511, 157
Leitherer, C., Schaerer, D., Goldader, J. D., et al. 1999, ApJS, 123, 3
Li, J.-T., Beck, R., Dettmar, R.-J., et al. 2016, MNRAS, 456, 1723
Li, Z., Shen, J., & Kim, W.-T. 2015, ApJ, 806, 150
Ma, C., de Grijs, R., & Ho, L. C. 2018, ApJ, 857, 116
Markoff, S. 2010, in Lecture Notes in Physics, ed. T. Belloni (Berlin: Springer), 143
Mazzuca, L. M., Knapen, J. H., Veilleux, S., et al. 2008, ApJS, 174, 337
Mezger, P. G., Duschl, W. J., & Zylka, R. 1996, A&ARv, 7, 289
Misiriotis, A., Papadakis, I. E., Kylafis, N. D., et al. 2004, A&A, 417, 39
Moon, S., Kim, W.-T., Kim, C.-G., et al. 2021, ApJ, 914, 9
Morris, M., & Serabyn, E. 1996, ARA&A, 34, 645
Murphy, E. J., Condon, J. J., Schinnerer, E., et al. 2011, ApJ, 737, 67
Perley, R. A., & Butler, B. J. 2013, ApJS, 204, 19
Piner, B. G., Stone, J. M., & Teuben, P. J. 1995, ApJ, 449, 508
Regan, M. W., Vogel, S. N., & Teuben, P. J. 1997, ApJL, 482, L143
Reynaud, D., & Downes, D. 1997, A&A, 319, 737
Rubin, V. C., Kenney, J. D. P., & Young, J. S. 1997, AJ, 113, 1250
Ryder, S. D., Knapen, J. H., & Takamiya, M. 2001, MNRAS, 323, 663
Seo, W.-Y., & Kim, W.-T. 2013, ApJ, 769, 100
Seo, W.-Y., Kim, W.-T., Kwak, S., et al. 2019, ApJ, 872, 5
Sorai, K., Kuno, N., Muraoka, K., et al. 2019, PASJ, 71, S14
Tabatabaei, F. S., Minguez, P., Prieto, M. A., et al. 2018, NatAs, 2, 83
Tabatabaei, F. S., Schinnerer, E., Murphy, E. J., et al. 2013, A&A, 552, A19
van der Laan, T. P. R., Schinnerer, E., Emsellem, E., et al. 2013, A&A, 551, A81
Vargas, C. J., Walterbos, R. A. M., Rand, R. J., et al. 2019, ApJ, 881, 26
Wiegert, T., Irwin, J., Miskolczi, A., et al. 2015, AJ, 150, 81
Yusef-Zadeh, F., Hewitt, J. W., Arendt, R. G., et al. 2009, ApJ, 702, 178