Extended Radio Structures and a Compact X-Ray Cool-core in the Cluster Source PKS 1353–341

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Abstract

We present a radio and X-ray study of PKS 1353–341, the brightest cluster galaxy radio source at the center of a recent Chandra-discovered X-ray cluster. Our multi-frequency Very Large Array images reveal an edge-brightened (FR-II), double-lobed structure with a total ~50 kpc extent, and 1.5 GHz power of $1.2 \times 10^{23}$ W Hz$^{-1}$, separated from the bright, arcsecond-scale core. We reanalyzed the Chandra data and found that the X-ray-emitting active galactic nucleus (AGN) is offset by ~9 kpc from a compact X-ray cool-core with temperature $kT = 3.1 \pm 0.5$ keV, and a radius of ~22 kpc, surrounded by a hotter $kT = 6.3 \pm 0.7$ keV gas out to ~50 kpc. The offset suggests sloshing inside the cool-core induced by a minor merger or a past outburst of the AGN that produced large-scale radio lobes. The comparable spatial scales of the lobes with the interface between the different temperature X-ray plasmas indicate the lobes are actively heating the outer layers of what is now a remnant compact cool-core. Our dual-frequency Very Long Baseline Array (VLBA) images reveal substructure in the central radio source, consisting of a radio core with double-sided parsec-scale jets pointing toward the kiloparsec-scale structures. The northern jet is detected only at 8.4 GHz, indicating its emission is behind an absorbing torus or disk. We also measured faster apparent motions in the southern jet up to 1.9 ± 1.1c than in the northern jet (0.8 ± 0.5c). While the VLBA observations indicate the southern jet is aligned slightly closer to our line of sight, the asymmetries are overall modest and imply minimal projection effects in the large-scale radio structures.

Key words: galaxies: active – galaxies: clusters: individual (PKS 1353–341) – galaxies: jets – radio continuum: galaxies – X-rays: general

1. Introduction

The radio source PKS 1353–341 is long known to be hosted by a large and luminous galaxy at redshift, $z = 0.223$ (White et al. 1988; Véron-Cetty et al. 2000). Because it is a bright (>0.5 Jy; Drinkwater et al. 1997) centimeter-wavelength flat-spectrum radio source, and its ROSAT-detected X-ray emission (Siebert et al. 1998) is attributable to the central active galactic nucleus (AGN), PKS 1353–341 has been considered a blazar candidate in all-sky catalogs (Healey et al. 2008; Massaro et al. 2009).

Recently, Somboonpanyakul et al. (2018) found through Chandra imaging that the bright X-ray-emitting AGN masked the presence of a massive extended X-ray cool-core galaxy cluster. The discovery was the outcome of their targeted search for overdensities of red galaxies around such ROSAT-detected AGNs (see also Green et al. 2017; Yang et al. 2018), and confirmed the underlying cluster indicated by the spatially coincident Planck Sunyaev–Zeldovich source PSZ2 G317.79 +26.63 (offset 1/7 from the radio position, thus within the 95% confidence error of 2/4; Planck Collaboration et al. 2016).

Thus, PKS 1353–341 can now be classified as a brightest cluster galaxy (BCG) hosting a radio- and X-ray bright AGN at the center of a luminous X-ray cluster.

Interestingly, the Chandra X-ray image of the cluster indicated a weak (2σ) signature of a pair of cavities at 8.5 kpc (~2.4) from the BCG (Somboonpanyakul et al. 2018). Because we found no published radio maps of PKS 1353–341 to compare to the X-ray data, this prompted us to investigate its radio properties using available archival multi-frequency data obtained over many years with the NRAO4 Very Large Array (VLA) and Very Long Baseline Array (VLBA).

The outcome of our study is summarized in the abstract. Section 2 contains the details of the VLA and VLBA data and our reanalysis of the Chandra data. In Section 3, the X-ray results are described and compared with the radio structures, while considering constraints on the system from the radio data on all spatial scales. A discussion and summary are given in Section 4.

All coordinates are given in J2000.0 equinox. The spectral index, $\alpha$, is defined as $F_{\nu} \propto \nu^{-\alpha}$. Uncertainties are quoted at the 68% confidence level.

2. Observations and Data Analysis

2.1. VLA Radio

The archival VLA data for PKS 1353–341 were obtained from 1983 to 2005 while the source was observed as a calibrator in a variety of array configurations (Table 1). These data sets utilized two 50 MHz wide intermediate frequencies centered at 1.5, 4.9, and 8.5 GHz. Pipeline processing was available for a majority of the cases from the NRAO VLA Archive Survey (NVAS)5 and these calibrated (u, v) files were used. Two data sets not in the NVAS (as indicated in Table 1) were downloaded from the NRAO archive and basic phase and

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3 Following Somboonpanyakul et al. (2018), we adopt $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $(\Omega_M, \Omega_{\Lambda}) = (0.3, 0.7)$, giving a distance of 1.1 Gpc, and angular scale of 3.6 kpc arcsec$^{-1}$ at the source redshift.

4 The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. The VLA is now named the Karl G. Jansky VLA.

5 http://archive.nrao.edu/nvas/
Table 1

Summary of the Archival VLA Data Sets

| Frequency (GHz) | Program$^a$ | Dates | Array$^b$ | Exposure (s) | $S_v$ (mJy)$^c$ |
|----------------|-------------|-------|-----------|-------------|----------------|
| 1.490          | API42       | 1987 Sep 30 | A | 280 | 602.4 |
| 1.425          | AK509       | 2002 Apr 8 | A | 250 | 567.3 |
| 4.860          | AT045       | 1983 Dec 19 | B/A | 1280 | 572.6 |
| 4.860          | AW136       | 1985 Jun 23 | B/C | 170 | 595.7 |
| 4.860          | AD224       | 1988 Oct 28 | A | 460 | 567.0 |
| 4.860          | AK509       | 2002 Apr 8 | A | 250 | 611.9 |
| 8.460          | AK509       | 2002 Apr 6, 8, 9, 10, 21; May 7 | A | 5220 | 703.7 |
| 8.460          | AK509       | 2002 May 21, 24, 27 | A/B | 2335 | 703.7 |
| 8.460          | AK509       | 2003 Feb 9 | D | 370 | 674.0 |
| 8.460          | AK583       | 2005 Jun 8 | B | 405 | 663.8 |

Notes.

$^a$ The two program data sets written in italics were manually calibrated using AIPS. The API42 data set used a 21 (out of 27) antenna subset of the array.

$^b$ Two letters indicate observations taken while antennas were moved between array configurations.

$^c$ Measured core flux densities in each data set.

gain calibration were performed using standard procedures in AIPS (Bridle & Greisen 1994).

After accounting for variability in the core (below) using UVSUB in AIPS, the $(u, v)$ data were combined with DCON to improve $(u, v)$ coverage and sampling over a range of spatial scales. The total integration times of the combined 1.5, 4.9, and 8.5 GHz data sets were 9, 36, and 139 minutes, respectively. The data were self-calibrated and imaged using the Caltech DIFMAP package (Shepherd et al. 1994) to produce the final images. Because of the southern decl. of the source, the resultant beam shapes of the images were highly elliptical (better east–west resolution). For ease of comparison with the X-ray images, the VLA data were reconvolved with circular beams with different sizes selected to display the structures visible in the CLEAN components.

To gauge variability in the core between the different data sets, flux densities were measured in the $(u, v)$ plane using DIFMAP’s modelfit program after an initial round of phase self-calibration was applied assuming an unresolved point source. Comparing measurements at 1.5 GHz and 4.9 GHz that used the same (A-) array revealed modest but significant variability of 6%–8% in the unresolved core flux densities between 1987/1988 and 2002. Because of the identical spatial scales sampled in these data, the variability was likely intrinsic to the source. In the nine 8.5 GHz data sets obtained in 2002 April and May (in A- and A/B-arrays), maximum excursions of only $-1.4%/+2.4\%$ from the average of 703.7 mJy were found, consistent with the $\sim1%$–2% systematic uncertainties expected in the absolute flux density scale (Perley & Taylor 2003); these data were thus combined and treated as a single data set with $\sim2$ hr total integration. A comparison of the data taken in different arrays indicated 2%–5% differences in the 4.9 and 8.4 GHz core flux densities over year timescales, with no systematic trend of increasing flux with decreased spatial resolution expected if the variability is due to unresolved intermediate-scale structures. Thus, for the purpose of combining the different data sets, we accounted for variability in the core to bring its flux (arbitrarily) to the scale of the 2002 April data at 1.5 and 8.5 GHz, and the 4.9 GHz data from 1983 December.

The main extended arcsecond-scale features in the VLA maps of PKS 1353–341 are seen in Figure 1 (left) and their measured parameters are summarized in Table 2. Outside of the arcsecond-scale radio core, the extended emission is dominated by a pair of edge-brightened lobes (oriented roughly north–south) with warps recessed from both lobe edges; a faint jet connects the core to the southern warpspot. For the compact features, we used DIFMAP’s modelfit program to fit Gaussian components to the data in the $(u, v)$ plane. Because the south jet and both extended lobes are resolved, with substantial substructure in the 4.9 and 8.5 GHz maps (see also, Section 3.2), their measurements were made in the map plane. For the features seen at all three frequencies, we found uncertainties in the spectral index of $\sim0.1$. All other features were detected in only the higher-resolution 4.9 and 8.5 GHz images, and we measured larger uncertainties in the index of $\sim0.3$.

2.2. VLBA Radio

PKS 1353–341 has been observed with the VLBA simultaneously at 2.3 and 8.7 GHz (dual-frequency mode) as part of the VLBA Calibrator Survey’s first (VCS-I; Fomalont et al. 2003) and second (VCS-II; Gordon et al. 2016) phases on 2002 January 31 and 2015 January 23, respectively. An additional third epoch imaging at 8.4 GHz was obtained on 2012 April 05 as part of a VLBA imaging survey of nearby radio-bright 2MASS galaxies (Condon et al. 2013). The observations each consisted of two short snapshot scans with total exposures of $\sim2$–5 minutes. The calibrated VLBA $(u, v)$ data and resultant maps from these programs are made publicly available in the Radio Fundamental Catalog (RFC; Petrov et al. 2019) and we downloaded them for further analysis.

The low decl. of the target resulted in elliptical beam shapes in the VLA images (e.g., Figure 1; right two panels), thus to facilitate a comparison, we reimaged all the data and reconvolved the images to a common circular beam size at each frequency. As seen in the resultant maps (Figure 2), the data were of varying sensitivity due to VLBA hardware improvements at more recent times. As expected (Gordon et al. 2016), the 2015 VCS data (200 s integration) were $\sim3$–5 $\times$ more sensitive than those in the first epoch in 2002 (300 s integration).

$^6$ The 2002, 2012, and 2015 VLBA data used in this work were contributed to the RFC website (http://astrosat.org/cgi-bin/mlbd_get_source.cgi?source=J1356-3421) by Y. Y. Kovalev, L. Petrov, and A. Pushkarev, respectively.
Figure 1. From left to right, radio images of PKS 1353–341 from kiloparsec scales to progressively smaller parsec scales. The VLA images (left panel) at 1.5 GHz (2″ beam) are shown in grayscale with green contours from the 4.9 GHz image (0.5 beam; levels from 0.25 to 2 mJy beam$^{-1}$ by factors of 2) overlaid. The main features on kiloparsec scales described in the text are labeled. In the next panels, the two deepest VLBA images from the RFC (see footnote 6) are shown centered on the core, at 2.3 GHz (middle; from 2015 January) and 8.4 GHz (right; from 2012 April), with colors plus contours at levels 1, 2, and 4 mJy beam$^{-1}$. The beamsizes are 7.1 mas $\times$ 2.8 mas (PA = $-1^\circ$) and 3.9 mas $\times$ 1.0 mas (PA = 6$^\circ$), respectively.

Figure 2. VLBA images of PKS 1353–341 rotated by 23$^\circ$ so the milliarcsecond-scale jets are aligned vertically on the figure. The left two panels are the 2.3 GHz images (4.5 mas beam) with contour levels increasing by factors of two from 8 to 64 mJy beam$^{-1}$. The right three panels are the 8.4/8.7 GHz images (2 mas beam) with contours increasing by factors of two up to 128 mJy beam$^{-1}$, beginning at 8, 1, and 4 mJy beam$^{-1}$ (from left to right). Identifiable features across epochs in the southern (S1, S2) and northern (N1, N2) jets are labeled.

Table 2

| Feature$^a$ | $d^b$ (′) | PA$^b$ (°) | $S_\nu$ (1.5 GHz) (mJy) | $S_\nu$ (4.9 GHz) (mJy) | $S_\nu$ (8.5 GHz) (mJy) | $\alpha$ |
|------------|-----------|------------|------------------------|------------------------|------------------------|---------|
| North lobe edge | 5.7 | $-5$ | ... | 8.6 $\pm$ 0.9 | 4.1 $\pm$ 0.4 | 1.3 $\pm$ 0.3 |
| North lobe | 5.0 | $-5$ | 34.7 $\pm$ 3.5 | 12.3 $\pm$ 1.2 | 6.3 $\pm$ 0.6 | 1.0 $\pm$ 0.1 |
| North warmspot | 3.9 | $-30$ | ... | 1.3 $\pm$ 0.1 | 0.8 $\pm$ 0.1 | 0.9 $\pm$ 0.3 |
| South jet | 3.3–5.1 | 158–161 | 4.6 $\pm$ 0.7 | 1.6 $\pm$ 0.2 | 0.9 $\pm$ 0.1 | 0.9 $\pm$ 0.1 |
| South warmspot | 6.4 | 163 | ... | 1.6 $\pm$ 0.2 | 1.0 $\pm$ 0.1 | 0.9 $\pm$ 0.3 |
| South lobe | 7.3 | 173 | 50.9 $\pm$ 5.1 | 16.7 $\pm$ 1.7 | 8.8 $\pm$ 0.9 | 1.0 $\pm$ 0.1 |
| South lobe edge | 7.7 | 173 | ... | 8.6 $\pm$ 0.9 | 5.2 $\pm$ 0.5 | 0.9 $\pm$ 0.3 |

Notes.

$^a$ The north and south lobe measurements at all frequencies include the respective lobe edges; the south lobe at 1.5 GHz includes its warmspot. The respective average sizes of the Gaussian fitted dimensions of the north and south lobe edges are ($r$, $a$, $\phi$) = (1$^{13}_{15}$, 0.4, 89$^\circ$) and (1$^{15}_{6}$, 0.5, 126$^\circ$), with the radius of the major axis ($r$), axial ratio ($a$), and position angle of the major axis ($\phi$).

$^b$ Angular distance ($d$) from the core and position angle (PA) defined as positive east of north.
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Table 3
Properties of the Milliarcsecond-scale Radio Features

| Feature | d (mas) | PA (°) | S_{uv} (mJy) | r (mas) | a (°) |
|---------|---------|--------|--------------|--------|-------|
| 8.7 GHz, 2002 Jan 31 |
| Core | 0 | 0 | 323.3 | 2.1 | 0.2 | -9 |
| N1 | 5.33 | -23.2 | 75.6 | 3.3 | 0.7 | 85 |
| 8.4 GHz, 2012 Apr 5 |
| Core | 0 | 0 | 248.5 | 3.4 | 0.2 | -9 |
| N1 | 5.78 | -24.4 | 120.2 | 3.6 | 0.4 | -4 |
| N2 | 16.34 | -22.4 | 45.0 | 3.7 | 0.2 | -7 |
| south | 6.16 | 164.4 | 44.1 | 0.9 | 1.0 | 0 |
| south | 10.59 | 152.4 | 31.5 | 3.0 | 1.0 | 0 |
| south | 18.19 | 151.4 | 10.6 | 0.8 | 1.0 | 0 |
| 8.7 GHz, 2015 Jan 23 |
| Core | 0 | 0 | 145.7 | 1.4 | 0.4 | -16 |
| N1 | 6.10 | -23.5 | 69.4 | 2.1 | 0.5 | 2 |
| N2 | 16.77 | -21.2 | 12.5 | 1.3 | 1.0 | 0 |
| south | 13.21 | 159.9 | 12.5 | 0.6 | 1.0 | 0 |
| 2.3 GHz, 2002 Jan 31 |
| Core | 0 | 0 | 152.2 | 2.5 | 1.0 | 0 |
| S1 | 9.83 | 153.7 | 97.7 | 4.1 | 0.2 | -19 |
| S2 | 20.00 | 153.8 | 101.1 | 2.8 | 1.0 | 0 |
| 2.3 GHz, 2015 Jan 23 |
| Core | 0 | 0 | 203.4 | 3.0 | 1.0 | 0 |
| S1 | 10.96 | 155.6 | 106.8 | 3.1 | 0.3 | -35 |
| S2 | 21.63 | 154.0 | 89.6 | 3.3 | 1.0 | 0 |

Note.
* Features in the north (N1, N2) and south (S1, S2) jets are given labels when they are readily identifiable between epochs; otherwise, the jet direction is noted. The remaining columns are as noted in Table 2.

integration), due to 4–12× greater bandwidths and higher recording rates. The 2012 data (135 s integration) were observed over the widest frequency range (7.9–8.9 GHz, centered at 8.4 GHz), resulting in better (u, v) coverage at short spacings, and thus standing out as having the best sensitivity to the extended structures.

We used DIFMAP’s modelfit to fit Gaussian components to the (u, v) data to give measured parameters of the different features (Table 3). Both 2.3 GHz images show a bright core with a single, prominent ~20 mas long jet pointing toward the southern kiloparsec-scale jet detected in the VLA images. At the same epochs, the 8.7 GHz images show a dominant core plus mainly a faint ~5–6 mas-distant knot to the north. The deeper 8.4 GHz image from 2012 detects both jets, confirming the northern extension up to ~17 mas hinted at in the 8.7 GHz image from 2015, and details the southern jet seen at 2.3 GHz. Estimates of the proper motions of the most distinct features are described in Appendix A and discussed in Section 3.3. The northern jet is notably absent in the 2.3 GHz images probably because it is behind a surrounding, central disk or torus, and its emission is more heavily absorbed at lower frequencies. Taken together, these observations—the likely absorption-implied orientation of the northern jet, the faster proper motions in the south jet (Appendix A), and the southern jet detection in the VLA images—imply the southern jet is aligned slightly closer to our line of sight (Section 3.3).

2.3. Chandra X-Ray

In light of the VLA detections of extended kiloparsec-scale radio emission, we reexamined the Chandra X-ray data set presented in Somboonpanyakul et al. (2018) that consisted of a 31 ks observation (ObsID 17214) with ACIS-I in very faint data mode. We reprocessed the level-1 ACIS event file using CIAO version 4.8 and the Chandra Calibration Database (CALDB) 4.8.0 following the procedure described in Vikhlinin et al. (2005). The light curve throughout the observation was inspected (see Markevitch et al. 2003) and we found no time intervals with significantly elevated background.

To obtain background-subtracted and exposure-corrected images of the cluster (Sections 3.1 and 3.2), we modeled the detector and sky background using the blank-sky data set from the CALDB appropriate for the date of observation, normalized using the ratio of the observed to blank-sky count rates in the 9.5–12 keV band. We also subtracted the ACIS readout artifact as described in Markevitch et al. (2000).

For regions of interest, we extracted spectra and generated the instrument responses ARF and RMF using the current calibration files for the telescope effective area, CCD quantum efficiency, and ACIS time-dependent low-energy contamination model. The emission from a 3″ radius region coinciding with the central X-ray AGN found by Somboonpanyakul et al. (2018) was excluded from our analysis of the extended cluster emission. For the same regions, we extracted the background spectra from the corresponding blank-sky data sets, normalized as described above. The spectra of the extended X-ray emission were fitted in XSPEC 12.9.0 with an absorbed, single-temperature APEC model in the 0.8–7 keV energy band, with the metal abundance left free to vary and the column density of H1 absorption fixed to the Galactic value of $5.57 \times 10^{20}$ cm$^{-2}$ (Kalberla et al. 2005).

3. Results

Here, we revisit the X-ray spatial and spectral analysis of the inner 100 kpc radius of the cluster emission that coincides with our newly found radio structures (Section 3.1). The X-ray results enable a comparison of the extended radio and X-ray structures (Section 3.2). We then discuss the VLBA observations of the inner unresolved radio core and parsec-scale jet features, including their measured apparent proper motions, in the context of the historical integrated radio spectrum (Section 3.3).

3.1. Central X-Ray Cluster Emission

A Chandra image in the 0.5–4 keV band is shown in Figure 3. We overlay a set of contours (from the same image) to show the finer structure in the X-ray emission in the central region of the map. The X-ray point source coinciding with the AGN (black contours) found by Somboonpanyakul et al. (2018) coincides with the radio core in our VLA and VLBA images. The white contours highlight the presence of a relatively compact region of radius ~22 kpc that encloses the brightest extended X-ray emission in the cluster center. The extended emission is brightest to the west of the X-ray AGN, and we find an offset of ~2″5 (~9 kpc) between its centroid (red cross) and the AGN.
In Figure 3(c), we show a *Chandra* X-ray radial surface brightness profile out to 100 kpc radius extracted with annular regions centered on the centroid of the extended emission, excluding a $r = 3''$ region around the AGN, using the full-resolution 0.5–4 keV image. There is a hint of a change in the surface brightness at $r \lesssim 22$ kpc (region 1), coincident with the bright central core we identified by eye in the X-ray image contours. Both the profile and image suggest a possible sharp brightness edge delineating an enhanced, inner compact core (at least in parts of the azimuth); however, the statistics are insufficient to rule out a smooth boundary.

We fitted the temperature (Section 2.3) of this compact core delineated by region 1 ($r = 22$ kpc) and the surrounding gas within region 2 (22 kpc < $r$ < 50 kpc) indicated in Figure 3(b).
The compact core is significantly cooler than the outer annulus, with (source rest-frame) temperatures of $kT = 3.1 \pm 0.5$ keV and $6.3 \pm 0.7$ keV, respectively (also reported in Figure 3(c)). The significantly different temperatures derived support the idea that the region within $\sim 22$ kpc is a physically distinct emission component from its surrounding annulus of $\sim 22-50$ kpc. These results also indicate that the PKS 1353–341 cluster lacks a large-scale cool-core, typically found in many relaxed clusters (e.g., Hudson et al. 2010). For the inner region 1, we found a $0.5-2.0$ keV luminosity, $L_X = (1.2 \pm 0.1) \times 10^{43}$ erg s$^{-1}$.

The X-ray surface brightness profile of the galaxy cluster studied by Somboonpanyakul et al. (2018, Figure 4, therein) was centered on the AGN, and is thus systematically offset by $\sim 2''5 = 9$ kpc from our profile that was centered on the compact, extended X-ray core. Because we found a significant offset between the AGN point source and the center of the compact core, we were able to study the details of the surface brightness profile at radii within 50 kpc, thus enabling the detection of the $kT \sim 3$ keV component within 22 kpc. According to their profile, the wings of the AGN point-spread function have only a small to negligible effect on our results because its surface brightness is at a $\sim 10 \times$ smaller level than the diffuse emission at the radius of $r = 3'' \sim 11$ kpc we used for its excision and drops rapidly with increasing distance. Their profile analysis extends out to radius $\gtrsim 1$ Mpc, and at radii from 50 kpc and greater, our profiles should be sufficiently similar to utilize their fitted results there. They found the statistics were sufficient to determine the temperature
profile from 50 to 700 kpc that appears consistent with a constant temperature, $kT \sim 8$ keV. At smaller radii (in the single bin analyzed from 10–50 kpc), they found a lower temperature of $\sim 5.5$ keV, consistent with our measurement in region 2.

3.2. Kiloparsec-scale Radio and X-Ray Emission

A Chandra X-ray image at softer energies (0.3–2 keV band) is presented in Figure 4 with the VLA radio contours at 1.5, 4.9, and 8.5 GHz overlaid. The main features visible in the X-ray map are the possible weak (2$\sigma$) X-ray decrements 2\°\:4 = 8.5 kpc from the AGN (marked with red circles in Figure 4) reported by Somboonpanyakul et al. (2018) that prompted our study of this system. These suspected cavities are found within the highest surface brightness X-ray emission of the central cluster emission characterized by the $kT \sim 3$ keV temperature. No radio emission is found inside the cavities in our images. In fact, the cavities’ axes ($PA = 15^\circ$ and 190\°) are misaligned with respect to the radio axes on the kiloparsec scale ($PA = -30^\circ$ and $-5^\circ$ to the north and 158°–173° to the south) and parsec scales ($PA = -23^\circ$ and 154\°). The cavities’ proximity to the cluster center, combined with the larger radial distance of the double-radio lobes, makes it unlikely that they are older relic ghost bubbles inflated by a past outburst of the AGN (e.g., Fabian 2012).

The pair of recessed, compact warmspots detected in the highest-resolution VLA images (0\".3) helps to define the radio source axis. While a faint jet points to the southern warmspot, the northern jet is undetected in our images. We call them warmspots (see Saunders et al. 1981) to emphasize that they are not high-brightness temperature features as seen in classical Fanaroff & Riley (1974) type-II (FR-II) radio doublets, but do seem to mark the active surface at the end of the kiloparsec-scale jets (e.g., Bridle et al. 1994, and references therein). The northern and southern warmspots do not have obvious counterparts in the optical images of Somboonpanyakul et al. (2018), so they are not obviously field radio sources. Note that in Véron-Cetty et al. (2000) there is an optical source near the BCG center that is a galaxy 4\°.8 to the N/NE at $PA = 19^\circ$ with the same redshift, but we find no radio counterpart to the source. Both lobe edges look edge-brightened and the northern one in particular looks shell-shaped, perhaps indicating enhanced interaction with the surrounding medium in this direction. The change in direction from the warmspots to the lobes gives the radio source an overall “Z”-shaped inverse symmetry that could indicate a precession of the central source, or could be due to interactions with the surrounding medium. The symmetry extends down to smaller scales (Section 3.3), with modest, but significant differences in position angles of the structures from kiloparsec to parsec scales of $\sim 7^\circ$ (north) and $\sim 4^\circ–9^\circ$ (south).

The limited statistics of the current Chandra exposure makes it difficult to determine if the X-ray surface brightness distribution in the two-dimensional map at radii $\geq 22$ kpc shows any significant features directly associated with the extended radio structures, particularly because the outer region is characterized by a hotter $kT \sim 6$ keV temperature (less soft photons). Broadly, spatial comparisons between the radio and X-ray emissions are likely minimally affected by projection effects (Section 3.3). We find the entirety of the southern lobe (angular distance of the inner to outer edges of $\sim 23$–28 kpc) lies just outside of the central $kT \sim 3$ keV emission, and is embedded in the hotter $kT \sim 6$ keV gas (Section 3.1). The north lobe edge at an angular distance of $\sim 21$ kpc coincides more closely with the interface of the between the central $kT \sim 3$ keV ISM and hotter surrounding gas. Otherwise, there is little sign of preferred enhanced activity/interaction of the radio jets and lobes with the surrounding gas.

The extended components found in the VLA 1.5 GHz image constitute $\sim 15\%$ of the total 1.5 GHz flux and the northern and southern lobes together correspond to a radio power of $1.2 \times 10^{25}$ W Hz$^{-1}$. The radio spectra of the lobes and their fainter features (jet, warmspots) are all consistent with a single power-law spectral index, $\alpha \sim 1$, in the VLA frequency bands (Table 2). As a prelude to the next subsection, it is interesting to try to reconcile the relationship between the integrated flux measurements at $< 1$ GHz frequencies seen in the integrated spectrum (Section 3.3) to consider the possible low-frequency extension of the spectra of these extended components. The low-frequency integrated spectrum from 74 to 200.5 MHz is consistent with a single power law ($\alpha = 0.55 \pm 0.12$), with the highest-resolution measurement taken at 25\″ from the GMRT TGSSADR (Appendix B). The spectrum extrapolates to the two 408 MHz integrated measurements, but underpredicts all the higher-frequency ones (Figure 5), indicating a separate spectral component at $> 1$ GHz dominated by the VLA core. Connecting the low-frequency (74–408 MHz) integrated spectrum to the spectrum of the extended VLA components would require a large break of $\Delta \alpha \sim 1.1$, meaning $\alpha (0.4–1.5$ GHz) $\sim 1.7$, that would be inconsistent with the $\alpha \sim 1$ found for the extended components at 1.5–8.5 GHz, amounting to a very unusual overall sawtooth spectral shape. Instead, we find the $> 1$ GHz integrated

![Figure 5](image.png)
measurements are actually a superposition of many unresolved sub-arcsecond-scale components (Section 3.3), thus favoring the interpretation that the VLBA-scale components’ spectra extend to lower energies. Indeed, extrapolating the 1.5–8.4 GHz spectra of the two lobes plus the southern jet with a single unbroken power law down to 74 MHz, and subtracting this from the integrated measurements defining the $\alpha = 0.55$ integrated component, we obtain a residual (dotted line in Figure 5) that shows a reasonable flat spectrum from 74 MHz to 43 GHz for the central, sub-arcsecond component. Taking the extrapolated total radio lobe flux at 150 MHz of 849 mJy, the total radio power, $L_{150 \text{ MHz}} = 1.2 \times 10^{26} \text{ W} \text{ Hz}^{-1}$ is on the upper end observed in systems with jet powers derived from X-ray cavities by Kokotanekov et al. (2017). Systems with similar or greater 150 MHz power have jet powers $\sim (1\text{--}70) \times 10^{44} \text{ erg s}^{-1}$, with a value of $3 \times 10^{44} \text{ erg s}^{-1}$ implied by the relation found in their ensemble sample.

### 3.3. The Central Radio Source

Existing radio studies of PKS 1353–341 were limited to published integrated flux measurements of the source (Somboonpanyakul et al. 2018). The NVSS 1.4 GHz flux density of 691.8 (±20.8) mJy (obtained in 1996 May) is consistent with our total VLA fluxes at the same frequency band (core fluxes in Table 1 plus extended fluxes in Table 2), and implies a total radio power of $1.0 \times 10^{26} \text{ W} \text{ Hz}^{-1}$.

Our compilation of all the integrated measurements of the source (Appendix B; Figure 5) shows a steep-spectrum component at low frequencies and a flat-spectrum component at $> 1$ GHz known from previous studies (e.g., Jauncey et al. 1982; Healey et al. 2008; Murphy et al. 2010). The overall radio spectrum appears to match one of the spectral templates of (Hogan et al. 2015, Figure 1, therein), with what initially appears to be a $> 1$ GHz gigahertz-peak spectrum (GPS; O’Dea 1998). However, our analysis in Section 3.2 demonstrated the spectrum of the unresolved arcsec-scale core that dominates the $> 1$ GHz emission likely extends down to the lowest-observed frequencies, indicating an underlying origin from a superposition of different aged emission features.

Indeed, our VLBA maps measured milliarcsecond-scale core fluxes at $\sim 2$–8 GHz that fall well below ($< 1/2$) the arcsecond-scale radio fluxes. Also considering the jet knots, a sum of all the VLBA-detected components (plotted in Figure 5) still lies below those of the unresolved arcsecond-scale VLA core flux density measurements, indicating there is further intermediate-scale emission not detected in these VLA data. Note the RFC database (See footnote 6) results indicate even finer-scale structure in these data with unresolved flux densities of 44–70 mJy at 8.4/8.7 GHz and 55–70 mJy at 2.3 GHz. While the arcsecond-scale core in our VLA data is mildly variable (up to 8%; Section 2), the 2.3/8.7 GHz spectrum of the milliarcsecond-scale core is strongly variable. The spectrum of the latter remained optically thick over the 13 yr, changing from being strongly inverted ($\alpha = -0.6$) to flat ($\alpha = 0.3$) mostly due to its decline in flux density at 8.7 GHz from $\sim 320 \text{ mJy}$ to $\sim 150 \text{ mJy}$.

The best 8.4 GHz image (Figure 2) detects both jets out to $\sim 20 \text{ mas}$ in both the north and south directions. While there appears to be an additional, very faint feature at $\sim 90 \text{ mas}$ (PA = $-15^\circ$) further to the north in the RFC 2.3 GHz map (Figure 1, center panel), the absence of the north jet in the 2.3 GHz images at smaller distances indicates the northern jet is apparently heavily absorbed at lower-frequency 2.3 GHz maps.

At the position of N2, we measured a 3$\sigma$ rms limit of $< 6 \text{ mJy}$ in the (deeper 2015) 2.3 GHz image, that translates to a constraint on the spectral index of $\alpha \lesssim -0.6$, consistent with a heavily absorbed spectrum. Note the AT20G catalog (Murphy et al. 2010) indicates very low polarization for the arcsecond-scale core, 1.1% at 8 GHz, and upper limits of $< 3.1\%$ at 20 GHz and $< 1.1\%$ at 5 GHz, confirming the presence of dense material in the inner regions.

With the long time baseline of the observations, we derived proper motions for the features in the VLBA maps that are identifiable between epochs (Appendix A). At 2.3 GHz, the VLBA images show the southern jet extends out to $\sim 20 \text{ mas}$, with the outer knot S2 moving radially outward (PA = 154$^\circ$) with apparent velocity, $\beta_{\text{app}} = v/c = 1.9 \pm 1.1$. The inner feature, S1, has more elongated structure in the maps, with marginal evidence of outward motion, $\beta_{\text{app}} \sim 1.3 \pm 1.2$, and no significant change in flux. The only measured proper motion in the north jet is for N1, at PA = $-24^\circ$, with $\mu = 0.055 \pm 0.034 \text{ mas yr}^{-1}$, implying that $\beta_{\text{app}} = 0.8 \pm 0.5$.

Assuming constant velocities over time, the inferred epochs of zero-separation (i.e., kinematic ages) of N1 and S1 are both $\sim 10^2 \text{ yr}$ prior to the first VLBA epoch in 2002, with ranges of 60–250 and 60–980 yr, respectively. Because of its larger proper motion, the more distant S2 knot gives a range of $(1\text{--}4) \times 10^2 \text{ yr}$ that is similar to the other features, and also helps to limit the upper uncertainty in the age of S1 (it must be younger than S2). Taking the respective proper motions of S1 and N1 as the approaching ($\mu_\text{a}$) and receding ($\mu_\text{r}$) jets, they provide only a weak constraint on the quantity (Rees 1966; Mirabel & Rodríguez 1999), $\beta_p \cos \theta = (\mu_\text{a} - \mu_\text{r}) / (\mu_\text{a} + \mu_\text{r}) = 0.24 \pm 0.51$, and thus unfortunately no useful constraints on the pattern velocity ($\beta_p$) and line-of-sight angle. Overall, the kinematic analysis indicates the parsec-scale structures are relatively young, with likely ages of the order of $\sim 10^2 \text{ yr}$.

Despite their large uncertainties, the modest values of the proper motions imply the parsec-scale structures lie close to the plane of the sky, consistent with the roughly symmetric brightnesses of the two jets in the deep 8.4 GHz image. We can infer from the faster motions in the southern milliarcsecond-scale jet and the possible absorption of the northern jet that the southern axis is slightly more closely aligned to our line of sight.

### 4. Discussion and Summary

We studied the kiloparsec- to parsec-scale radio structures of PKS 1353–341 ($z = 0.223$), the BCG at the center of a recently discovered X-ray cool-core cluster by Somboonpanyakul et al. (2018). Our VLA images reveal the large-scale radio emission exhibits an edge-brightened (FR-II) radio morphology. They have a radio power at 1.5 GHz of $1.2 \times 10^{25} \text{ W} \text{ Hz}^{-1}$, that is near the dividing line between FR-I and -II (Wold et al. 2007; Cheung et al. 2009). FR-II radio sources at the centers of nearby clusters are relatively rare, being found in <1% of Abell clusters at $z < 0.25$ (Owen et al. 1992; Owen & Ledlow 1997; Stawarz et al. 2014; Hagino et al. 2015); see also, e.g., Cygnus A (e.g., Arnaud et al. 1984; Smith et al. 2002). Taking the FR-II classification together with the optical spectrum of the AGN with narrow emission lines typical of a Seyfert type-2 galaxy (Véron-Cetty et al. 2000), makes it best classified as a narrow-line radio galaxy (Veilleux & Osterbrock 1987); see also Curran et al. (2006).
On parsec scales, the VLBA-observed emission consists of a two-sided jet aligned toward the kiloparsec-scale structures, and centered on a flat-spectrum radio core. The detection of the northern jet at only a higher frequency is analogous to other well-studied radio galaxies where the faintness of the counter jet at lower frequencies is associated with free–free absorption due to the presence of a torus or disk (e.g., Krichbaum et al. 1998; Walker et al. 2000). Indeed, such a torus or disk with a radius of tens of parsecs or more was indicated in the detected H I away from our line of sight (Véron-Cetty et al. 2000). The inferred absorption of the northern jet makes it likely to be the counter jet (aligned away from our line of sight), consistent with its smaller (sub-luminal) proper motions, $\beta_{app} = 0.8 \pm 0.5$, rather than what is observed in the southern jet (maximum of $\beta_{app} = 1.9 \pm 1.1$).

Our reanalysis of the spatial and spectral properties of the central 100 kpc of the X-ray cluster in the Chandra data suggest the presence of a central bright X-ray structure with a radius, $r \approx 22$ kpc, and temperature of $\sim 3$ keV. Despite being contained within the optical extended envelope of the host BCG that is known to be particularly large (extent $\geq 400$ kpc) and luminous (Véron-Cetty et al. 2000), with $L_K/L_{\odot} = 1.6 \times 10^{12}$ (for $K_s$-band magnitude of 13.1; Skrutskie et al. 2007), the feature is inconsistent with being a galactic corona. This is because of its large size, and its temperature is too high compared to the hottest temperatures ($1.5–2$ keV; Sun et al. 2007) observed in galactic coronae associated with the most massive elliptical galaxies. The most similar dense cool-core system was found in A2107 by Sun et al. (2007), with $r \approx 18$ kpc and $kT \approx 2.7$ keV, who suggested this hot and large component (see also Fujita et al. 2006) was most likely associated with the cluster cool-core.

Overall, the limited statistics of the current Chandra exposure make it difficult to determine if there is significant X-ray substructure that may be associated with the finer details seen in the radio images. Near the center of the cluster, we found no radio emission coincident with the weak $\sim 2\sigma$ X-ray decrements at $\sim 8.5$ kpc from the AGN found in the Chandra images (Somboonpanyakul et al. 2018) that could support their interpretation as cavities. Instead, the radio lobes in PKS 1353–341 appear to be located just outside the X-ray cool-core (Section 3.2), a feature commonly found in cluster coronae with lower-power FR-I radio sources (e.g., Krawczynski et al. 2003; Hardcastle et al. 2005; Sun et al. 2005). This anti-correlation of the radio and X-ray emission in the FR-I/corona systems could indicate the innermost kiloparsec-scale jets in these systems do not significantly heat the coronae at smaller radii, but rather deposit the bulk of their energy at larger scales (Sun et al. 2007).

The 0.5–2 keV luminosity of the $r = 22$ kpc cool-core in PKS 1353–341, $L_X = (1.2 \pm 0.1) \times 10^{44}$ erg s$^{-1}$ and its radio luminosity of $1.0 \times 10^{26}$ W Hz$^{-1}$ from the total NVSS 1.4 GHz flux density, make it one of the most radio-luminous objects of the cool-core class (Sun 2009, Figure 1). At the same time, the X-ray size is smaller than the typical cool-cored in clusters found in more nearby systems, and the cool-core is displaced $\sim 2/5$ ($\sim 9$ kpc) west of the AGN at the center of the cluster (Somboonpanyakul et al. 2018). The offset suggests gas motions (sloshing) inside the cool-core that can be induced by a gravitational perturbation of the cluster caused by a minor merger (e.g., Markovich & Vikhlinin 2007). The central AGN outburst may also contribute to sloshing by supplying kinetic energy to the surrounding cool gas (Markovich et al. 2001; Quilis et al. 2001; Hlavacek-Larrondo et al. 2011). In this case, a preexisting asymmetry in the X-ray gas distribution is likely needed to explain the different orientation of the radio outburst and the direction of the cool-core offset. Detailed simulations of AGN outbursts in asymmetric cool-cores would be required to explore this possibility. The AGN outburst could have heated the outermost layers of the cool-core, leaving a compact, cool-core remnant (Sun et al. 2004) as we observe. Sloshing may have further contributed to heating up the gas by facilitating heat inflow to the core (Zhong et al. 2010). This provides a picture consistent with the similar angular scales of the observed small, offset, compact X-ray cool-core and the $\sim 20$ kpc scale of the large-scale FR-II radio lobes revealed in the VLA maps.

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Facilities: Chandra (ACIS), VLA, VLBA.
Software: AIPS (Brice & Greisen 1994), CIAO (Fruscione et al. 2006), DIFMAP (Shepherd et al. 1994), SAOImage DS9 (Joye & Mandel 2003), XSPEC (Dorman & Arnaud 2001; Dorman et al. 2003).

Appendix A

VLBA Proper Motions

The long, 13 yr time period spanned by the VLBA observations allows us to measure or useful constrain the proper motions for common features in the southern jet seen in the 2.3 GHz images (S1 and S2) and in the northern jet seen in the 8.4/8.7 GHz images (N1 and N2). Their measured displacements relative to the core (Table 3) are plotted versus time in Figure 6. For the purpose of this analysis, uncertainties in the knot positions were assumed to be 1/6 of the common beam-widths (see, e.g., Lister et al. 2009, and references therein) in the maps presented in Figure 2. At the source redshift, 0.07 mas yr$^{-1} = 1c$. The feature N1 is identifiable in all three 8.4/8.7 GHz data sets, with clear proper motion detected. It is moving radially outward from the core at an average PA $= -24^{\circ}$, with $\mu = 0.055 \pm 0.034$ mas yr$^{-1}$, implying an apparent motion, $\beta_{app} = v/c = 0.8 \pm 0.5$ for N1.

The remaining features are observed only in two epochs. The southern jet is detected only in the 2.3 GHz images with a larger beam size than the ones at 8.7 GHz, and thus require larger proper motions for significant detections. Indeed, the largest proper motion is observed in the outer knot S2, moving along PA $= 154^{\circ}$ at a rate, $\mu = 0.13 \pm 0.08$ mas yr$^{-1}$, that implies apparent superluminal motion, $\beta_{app} = 1.9 \pm 1.1$.

The inner knot S1 has apparent substructure in the 4.5 mas resolution 2.3 GHz images and the resultant fitted Gaussian component is elongated along the jet direction. There is a fitted component in the 2 mas resolution 8.4 GHz image in the 2012 data whose position would be consistent with S1 seen at 2.3 GHz, but the additional elongated substructure in the higher-resolution image complicates the component identification and centroid measurement. With the two 2.3 GHz measurements, the proper motion is formally, $\mu \sim 0.09 \pm 0.08$ mas yr$^{-1}$ (PA $\sim 155^{\circ}$), and would imply a superluminal motion as well, $\beta_{app} \sim 1.3$. 
Finally, the fainter, outer feature in the north jet, N2, is seen only in the latter two epochs. Its measurements are consistent with zero displacement (∼0.4 ± 0.5 mas) along PA ∼ −22°, which implies an upper limit of μ < 0.32 mas yr⁻¹ (1σ).

### Appendix B

#### Historical Integrated Radio Spectrum

The integrated radio measurements of PKS 1353–341 are compiled from published data (Table 4) predominantly from NED. Additional simultaneous measurements in 1997 January from the VLA Calibrator Manual (Perley & Taylor 2003) are listed separately. The data are plotted in Figure 5.

A single-band measurement at 151 MHz of 1.579 ± 0.065 Jy was given for GLEAM J135605–342110 by Hurley-Walker et al. (2017), consistent with the 150 MHz GMRT measurement from the TGSSADR catalog (Intema et al. 2017). The GLEAM data, however, were obtained over a wide band, 72–231 MHz, and we measured the flux densities in four separate band images (72–103, 103–134, 139–170, and 170–231 MHz), obtained by Gaussian fits using JMFIT in AIPS. The measurements are presented at their corresponding central frequencies, with errors computed by adding a 5% flux calibration uncertainty and the local image rms in quadrature. The individual band flux densities are mostly in line with other low-frequency measurements, except that the 87.5 MHz point is somewhat high, but the low-frequency spectral index seems overall consistent with α ∼ 0.5. Taking the most-modern lowest-frequency measurements from the VLSSr 74 MHz (75″ beam), TGSS 150 MHz (25″), and our three reliable GLEAM measurements at 118.5 (∼3″/5), 154.5 (∼2″/6), and 200.5 MHz (∼2″/2), the best-fit spectral index is α = 0.55 ± 0.12.

#### Table 4

| Frequency (GHz) | Sₜ (mJy) | Catalog Name* |
|----------------|----------|---------------|
| 20             | 431 ± 21 | AT20G J135605–342111 |
| 8.6            | 724 ± 36 | AT20G J135605–342111 |
| 8.4            | 708 ± 70.8 | CRATES J135604–342041a |
| 5              | 670 ± 67 | PKS J1356–3421a |
| 4.85           | 731 ± 52 | PMN J1356–3420 |
| 4.8            | 690 ± 34 | AT20G J135605–342111 |
| 2.7            | 604 ± 64 | PKS J1356–3421a |
| 2.3            | 560 ± 13.7 | SPASS J135603–342101 |
| 2.29           | 640 ± 64 | Jauncey et al. (1982) * |
| 1.4            | 691.8 ± 20.8 | NVSS J135605–342110 |
| 1.4            | 692 ± 69.2 | AT20G-harc J135605–342111a |
| 0.843          | 843.2 ± 25.4 | SUMSS J135605–342109 |
| 0.365          | 1341 ± 104 | TXS J1353–341 |
| 0.408          | 940 ± 94 | PKS J1356–3421a |
| 0.408          | 900 ± 70 | MRC 1353–341 |
| 0.2005         | 1292 ± 68 | GLEAM J135605–342110/ |
| 0.1545         | 1513 ± 84 | GLEAM J135605–342110/ |
| 0.135          | 1516.5 ± 151.9 | TGSSADR J135605.3–342109 |
| 0.1185         | 1760 ± 122 | GLEAM J135605–342110/ |
| 0.0875         | 2797 ± 168 | GLEAM J135605–342110/ |
| 0.074          | 2160 ± 300 | VLSr J135604.8–342114 |
| 43             | 240 ± 24 | VLA Calibrator Manual* |
| 15             | 600 ± 60 | VLA Calibrator Manual* |
| 8.1            | 690 ± 69 | VLA Calibrator Manual* |
| 5              | 780 ± 78 | VLA Calibrator Manual* |
| 1.5            | 680 ± 68 | VLA Calibrator Manual* |

#### References

- AT20G (Murphy et al. 2010), AT20G-harc (Chhetri et al. 2013), CRATES (Healey et al. 2007), GLEAM (Hurley-Walker et al. 2017), Jauncey et al. (1982), MRC (Large et al. 1981), NVSS (Condon et al. 1998), PKS (Wright & Otrupcek 1990), PMN (Wright et al. 1994), SPASS (Meyers et al. 2017), SUMSS (Mauch et al. 2003), TGSSADR with GMRT (Intema et al. 2017), TXS (Douglas et al. 1996), and VLSSr (Lane et al. 2014) from https://www.cv.nrao.edu/vlss/VLSSlist.shtml.

Note. *Catalogs/Names indicated with asterisks did not quote uncertainties, and 10% was assumed here.

Note that there is a known field radio source, NVSS J135553–341842, to the NW of PKS 1353–341, but we found no other radio detections of this faint source (8.3 ± 0.5 mJy at 1.4 GHz) in the other catalogs. The 3′6 offset between the sources is larger than the beam sizes in the lower-frequency maps, and the NVSS source is likely too faint to have contributed to the integrated flux measurements of PKS 1353–341.

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