Mid-infrared Excess from the West Hot Spot of the Radio Galaxy Pictor A
Unveiled by WISE

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Abstract

Mid-infrared properties are reported of the west hot spot of the radio galaxy Pictor A with the Wide-field Infrared Survey Explorer (WISE). The mid-infrared counterpart to the hot spot, WISE J051926.26–454554.1, is listed in the AllWISE source catalog. The source was detected in all four of the WISE photometric bands. A comparison between the WISE and radio images reinforces the physical association of the WISE source to the hot spot. The WISE flux density of the source was carefully evaluated. A close investigation of the multi-wavelength synchrotron spectral energy distribution from the object reveals a mid-infrared excess at the wavelength of $\lambda = 22\mu m$ with a statistical significance of $4.8\sigma$ over the simple power-law extrapolation from the synchrotron radio spectrum. The excess is reinforced by single and double cutoff power-law modeling of the radio-to-optical spectral energy distribution. The synchrotron cutoff frequency of the main and excess components was evaluated as $7.1 \times 10^{14}$ Hz and $5.5 \times 10^{13}$ Hz, respectively. From the cutoff frequency, the magnetic field of the emission region was constrained as a function of the region size. In order to interpret the excess component, an electron population different from the main one dominating the observed radio spectrum is necessary. The excess emission is proposed to originate in a substructure within the hot spot, in which the magnetic field is a factor of a few stronger than that in the minimum-energy condition. The relation of the mid-infrared excess to the X-ray emission is briefly discussed.

Key words: acceleration of particles – galaxies: individual (Pictor A) – galaxies: jets – infrared: galaxies – radiation mechanisms: non-thermal

1. Introduction

Radio galaxies with an FR II morphology (Fanaroff & Riley 1974) usually host compact bright synchrotron radio structures, called hot spots (e.g., Begelman et al. 1984), at the terminal region of their jets. It is widely believed that the hot spots correspond to a strong shock created by the jet interaction with the ambient intergalactic medium. In the hot spots, particles are accelerated into the relativistic energies via the diffusive shock acceleration, usually called the first-order Fermi process (e.g., Meisenheimer et al. 1989, 1997). Thus, they are considered as a possible production site of high-energy cosmic rays (e.g., Hillas 1984). However, the detailed physical conditions in the hot spots are under debate, and therefore observational constraints are indispensable for exploring the particle acceleration mechanism in detail.

Previously, a combination of radio and X-ray spectral information has been one of the most valuable probes for the physical properties of the hot spots (e.g., Hardcastle et al. 2004). Within a framework of the one-zone particle acceleration, the hot spots are divided into two classes, based on the possible radiation mechanism for the X-ray photons. The X-ray spectrum from the high-luminosity hot spots is successfully interpreted by the synchrotron-self-Compton (SSC) process under a magnetic field close to the equipartition value. In contrast, the high-

frequency tail of the synchrotron emission tends to significantly contribute to the X-ray spectrum of the low-luminosity hot spots. However, in order to derive a more definite conclusion, spectral information in between the radio and X-ray bands is usually very useful.

Mid-infrared observations have the potential to shed light on this issue, by filling this wide frequency gap. A pioneering mid-infrared observation of the FR II radio galaxy Cygnus A with the Spitzer observatory strengthened the SSC scenario for its archetypal high-luminosity hot spots (Stawarz et al. 2007). However, the Spitzer upper limit on the mid-infrared flux of several low-luminosity hot spots seems inconsistent with the simple one-zone synchrotron interpretation for their radio-to-X-ray spectral energy distribution (Werner et al. 2012). Utilizing the mid-infrared data, Kraft et al. (2007) claimed that two independent synchrotron-emitting electron populations are required to reproduce the wide-band spectral energy distribution from the host spots of the radio galaxy 3C 33. The double synchrotron interpretation was invoked for the infrared knots of the jet in the quasar 3C 273 (Uchiyama et al. 2006). The multi-component interpretation was applied to the polarimetric properties observed with the Atacama Large Millimeter/submillimeter Array (ALMA) from kiloparsec-scale structures associated with the hot spot of 3C 445 (Orienti et al. 2017). Thus, the mid-infrared observations have gradually revealed that the acceleration phenomena in the hot spots are
actually complicated and heterogeneous rather than the simple one-zone Fermi acceleration.

In order to extend the mid-infrared knowledge on the host spots, the science products from the Wide-field Infrared Survey Explorer (WISE; Wright et al. 2010) are expected to be one of the ideal tools. WISE covers a wide mid-infrared range with the four photometric bands at the wavelengths of $\lambda = 3.4$ (W1), 4.6 (W2), 12 (W3), and 22 $\mu$m (W4). In particular, the AllWISE source catalog, which was constructed by a combination of the data obtained in the cryogenic and post-cryogenic (Mainzer et al. 2011) phases, is useful since it tabulates more than 747 million objects, thanks to its all-sky coverage with a relatively high sensitivity (e.g., $54 \mu$Jy at 3.4 $\mu$m).

The FR II radio galaxy Pictor A, located at a redshift of $z = 0.035$ (Eraceulose & Halpern 2004), is known to host a distinctive radio hot spot at the edge of its west lobe (e.g., Perley et al. 1997). It is known as a representative of low-luminosity hot spots (Hardcastle et al. 2004). Thanks to its high radio intensity, the object has been extensively studied not only in the radio band, but also in the near-infrared (Meisenheimer et al. 1997), optical (Thomson et al. 1995), and X-ray (e.g., Wilson et al. 2001; Hardcastle et al. 2016) frequencies. The high-resolution radio image derived with the Very Long Baseline Array (VLBA) resolved the hot spot into parsec-scale substructures (Tingay et al. 2008). The hot spot is included in the Spitzer hot spot sample by Werner et al. (2012). However, their result at 24 $\mu$m seems inconsistent with that of Tingay et al. (2008), despite using the same data set.

In the present paper, the mid-infrared properties of the west hot spot of Pictor A are investigated with WISE. The mid-infrared spectrum exhibits a significant excess over the simple extrapolation of its power-law (PL) radio spectrum. The excess strongly requires an additional population of synchrotron electrons.

Referring to the previous study (Tingay et al. 2008), the cosmological constants are assumed to be $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.27$, and $\Omega_{\Lambda} = 0.73$ (Spergel et al. 2003). These yield an angle-to-size conversion factor of 688 pc/1" at the rest frame of Pictor A.

### Table 1

| Band | $\lambda$ ($\mu$m)$^a$ | SN$^b$ | $m$ (mag)$^e$ | $F_{\lambda}$ (mJy)$^d$ | $\sigma_{sys}$ (mJy)$^f$ | $f_\text{c}^g$ | $f_\text{d}^h$ |
|------|-----------------|-----|----------|----------------|-----------------|---------|---------|
| W1   | 3.35            | 45.8| 13.368 ± 0.024 | 1.39 ± 0.03 | 0.03             | 0.992   | 1       |
| W2   | 4.60            | 50.2| 12.324 ± 0.022 | 2.02 ± 0.04 | 0.06             | 0.994   | 1       |
| W3   | 11.56           | 35.7| 9.569 ± 0.03  | 4.60 ± 0.13 | 0.21             | 0.937   | 1       |
| W4   | 22.09           | 13.1| 7.215 ± 0.083 | 9.98 ± 0.76 | 0.57             | 0.993   | 0.92    |

Notes.

$^a$ The isophotal wavelength of the WISE photometric band.

$^b$ The signal-to-noise ratio.

$^c$ The source magnitude in the Vega unit.

$^d$ The corresponding flux density.

$^e$ The systematic error of the WISE photometry (Jarrett et al. 2011).

$^f$ The color-correction factor for $\alpha = 1$.

$^g$ The additional correction factor for red sources (see Wright et al. 2010).

### 2. Data Analysis

#### 2.1. WISE Counterpart to the West Hot Spot of Pictor A

From the AllWISE source catalog, a moderately bright source, WISE J051926.26–454554.1, was identified as the mid-infrared counterpart to the west hot spot of Pictor A. The WISE properties of the source are listed in Table 1. Among the five photometric measurements in the catalog, the deep detection profile-fit photometry is adopted. The source is detected at all four WISE photometric bands with a high signal-to-noise ratio (>5). The flag information in the catalog indicates that the source is point-like (ext_flag = 00000), its photometric quality is high (ph_flag = AAAAA), it probably exhibited no intensity variation during the WISE survey (var_flag = 2111), and it is not contaminated by known artifacts (cc_flags = 0000).

Figure 1 shows the WISE image of WISE J051926.26–454554.1 at $\lambda = 3.4$ $\mu$m. The unpublished 4.8 GHz radio image obtained with the Australia Telescope Compact Array (ATCA; kindly provided by Dr. E. Lenc 2017, private communication) is overlaid with contours. The figure supports the physical association of the WISE source with the hot spot, rather than with the radio filament in the southeast (Röser & Meisenheimer 1987). Considering the source density in this field, the probability of the chance of coincidence is low.

The WISE and ATCA coordinates were more precisely registered by analyzing the nucleus of Pictor A. The WISE position of the nucleus is found to agree with its ATCA peak within $\sim$20 mas. Since this is smaller than the systematic uncertainty of the WISE astrometry, $\sim$50 mas, no astrometric correction was performed. Then, the offset of the WISE position of the hot spot to the ATCA one was evaluated as, at most, $\sim$300 mas toward the southeast, i.e., the direction to the jet. The X-ray position of the hot spot was reported to be shifted by $\sim$1" from the radio peak (Hardcastle et al. 2016) in a similar direction.

#### 2.2. Mid-infrared Spectrum

By referring to Wright et al. (2010), the flux density of the west hot spot at a frequency $\nu = \frac{\lambda}{c}$ of the WISE photometric

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9 Electronically available at http://irsa.ipac.caltech.edu/cgi-bin/Gator/nph- scan?submit=Select&project=WISE.

10 See “Explanatory Supplement to the AllWISE Data Release Products,” which is electronically available at http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/index.html.
Figure 1. 3.4 μm WISE image around the west hot spot of Pictor A (colorscale in units of μJy pix⁻¹). The pixel size of the image is 1′375 × 1′375 The 4.8 GHz ATCA image is superposed with contours, drawn at 10 levels from 0.018 to 1.8 Jy beam⁻¹ in the logarithmic scale. The ellipse at the top shows the ATCA beam size. The hot spot and filament (Roser & Meisenheimer 1987) are indicated by the arrows. The horizontal arrow at the top right indicates the angular scale of 10″, which corresponds to the physical scale of 6.88 kpc at the rest frame of Pictor A.

The spectral energy distribution of the hot spot from the 3.4 μm WISE band is evaluated as

\[ F_\nu = \frac{f_c}{f_c} F_0^\alpha \times 10^{-\frac{m}{c}}, \]

where \( c \) is the light speed, \( m \) is the WISE magnitude, \( F_0^\alpha \) is the zero-magnitude flux density for a PL-like spectrum with the energy index of \( \alpha = 2 \) (\( F_\nu \propto \nu^{-\alpha} \)), \( f_c \) is the color-correction factor, and \( f_l \) is the additional color-correction factor for a red source (\( \alpha \gg 1 \)) only applied to the 22 μm flux density. Based on the observed WISE color (e.g., \( m(3.4) - m(4.6) = 1.04 \)), the color correction for \( \alpha = 1 \) was applied. The Galactic extinction correction was negligible because it is estimated to be less than 1% even at 3.4 μm from the B-band extinction of \( A_B = 0.186 \) (Schlegel et al. 1998) and the standard extinction law (Rieke & Lebofsky 1985). The flux density of the source is summarized in Table 1, together with the adopted \( f_c \) and \( f_l \) values. The systematic uncertainty in the WISE flux density, \( \sigma_{\text{sys}} \), was based on Jarrett et al. (2011).

Figure 2 displays the WISE spectrum of the west hot spot at \( \nu = (1.3-9.0) \times 10^{13} \) Hz (i.e., \( \lambda = 3.4-22 \) μm). The spectrum exhibits no break or cutoff in the WISE range. It is successfully approximated by a PL model (the dashed line in Figure 2), and its index, \( \alpha = 0.97 \pm 0.05 \), becomes self-consistent to the observed WISE color, adopted for color correction.

2.3. Spectral Energy Distribution

The spectral energy distribution of the hot spot from the radio-to-optical frequencies is compiled in Figure 3. The WISE data are displayed with circles. The published data measured with Spitzer are also plotted with boxes. Tingay et al. (2008) and Werner et al. (2012) independently reported the results from the same Spitzer observation. Their photometric measurements coincide with each other in the 3–8 μm range within ~10%, while their results differ at 24 μm by ~30%, possibly due to the difference in their photometric aperture. In the present paper, the Spitzer spectrum by Werner et al. (2012) is utilized because their 24 μm flux is in good agreement to the 22 μm WISE flux, as is seen from Figure 3. The radio, near-infrared, and optical data, indicated by diamonds, are taken from Meisenheimer et al. (1997).

The object exhibits a straight PL radio spectrum over nearly three orders of magnitude in the 330 MHz–230 GHz range. The best-fit flux density at 5 GHz and energy index were, respectively, evaluated as \( F_\nu = 2.20 \pm 0.02 \) Jy and \( \alpha = 0.74 \pm 0.015 \) (Meisenheimer et al. 1997). As shown with the hatched tie in the top panel of Figure 3, its simple extrapolation to the higher frequencies intersects the mid-infrared spectrum in the WISE/Spitzer frequency range around \( \nu = 5 \times 10^{13} \) Hz (i.e., \( \lambda \sim 6 \) μm). The near-infrared to optical spectrum in the range of \( \nu \gtrsim 10^{14} \) Hz is steeper than the mid-infrared one, indicating a spectral cutoff.

It is important to note that the object shows a PL mid-infrared spectrum with \( \alpha \sim 1 \) even at the lower frequency range \( \nu < 5 \times 10^{13} \) Hz. Thus, the 22 μm WISE flux density exceeds the extrapolation of the radio spectrum by 3.7 mJy. The significance of this excess is evaluated as 4.8σ. Even if the systematic uncertainty of the WISE photometry (i.e., \( \sigma_{\text{sys}} = 0.57 \) mJy at 22 μm) is taken into account, the excess remains meaningful (~3.8σ). The result is fully supported by the 24 μm Spitzer data.

2.4. Spectral Modeling of the Mid-infrared Excess

First, the radio-to-optical spectral energy distribution observed from the west hot spot of Pictor A was fitted with a single cutoff–PL model. For the mid-infrared data, only those with WISE were utilized. To compensate possible interband flux calibration uncertainties, the systematic error on the WISE photometry (i.e., \( \sigma_{\text{sys}} \)) was taken into account. The resultant spectral parameters are summarized in Table 2. The energy index and flux density, \( \alpha = 0.73 \pm 0.01 \) and \( F_\nu = 2.24 \pm 0.07 \) Jy at 5 GHz, both agree with those of the radio spectrum in the 330 MHz–230 GHz range (see
Second, a double cutoff–PL model was fitted to the observed spectrum, in order to quantify the excess spectrum. The main component aims to describe the normal synchrotron radiation dominating the radio-to-optical spectrum, while the other component is introduced to approximate the mid-infrared excess. The best-fit model is shown with the solid line in the bottom panel of Figure 3, and its spectral parameters are tabulated in Table 2. The observed spectrum was reasonably reproduced by the model ($\chi^2$/dof = 2.3), and thus the deviation of the model becomes insignificant for all of the data points. Therefore, the the double cutoff–PL fitting rather than the single cutoff–PL one seems more preferable.

The energy index and cutoff frequency of the main component were constrained as $\alpha = 0.78 \pm 0.02$ and $\nu_c = (7.1 \pm 2.2) \times 10^{14}$ Hz, respectively. The main component becomes slightly softer than the single cutoff–PL model, and hence the PL model to the radio spectrum, probably due to the excess component. In the mid-infrared band, the excess component (the thick dashed line in Figure 3) has a similar contribution to that of the main component (the dashed–dotted line). The excess component exhibits a hard index of $\alpha = 0.40 \pm 0.14$, which is consistent with the prediction from the strong shock limit ($\alpha = 0.5$). The cutoff frequency of the excess component, $\nu_c = (5.5 \pm 1.8) \times 10^{13}$ Hz, is lower by an order of magnitude than that of the main component.

### 3. Discussion

#### 3.1. Summary of the Mid-infrared Excess

The west hot spot of the FR II radio galaxy Pictor A was identified as the mid-infrared source, WISE J051926.26–454554.1, listed in the AllWISE source catalog. A comparison of the WISE and ATCA images confirms that the mid-infrared source corresponds to the radio peak of the hot spot rather than the filamentary structure on the southeast (Röser & Meisenheimer 1987). After carefully evaluating the WISE flux density (see Table 1), the mid-infrared energy index of the hot spot was evaluated as $\alpha = 0.97 \pm 0.05$. Figure 3 indicates that the 22 $\mu$m WISE flux density significantly exceeds the simple extrapolation of the radio PL spectrum with an index of $\alpha = 0.74 \pm 0.015$. The excess is reinforced by the

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### Table 2

| Component | Parameter     | Single Cutoff–PL Model | Double Cutoff–PL Model |
|-----------|---------------|------------------------|------------------------|
| Main      | $F_c$(5 GHz)  | 2.24 ± 0.07            | 2.00 ± 0.14            |
|           | $\alpha$ (Jy$^{-1}$) | 0.73 ± 0.01            | 0.78 ± 0.02            |
|           | $\nu_c$ (Hz)$^b$ | (3.7 ± 0.4) $\times$ 10$^{14}$ | (7.1 ± 2.2) $\times$ 10$^{14}$ |
| Excess    | $F_c$(22 $\mu$m) | ...                   | 5.1 ± 1.1              |
|           | $\alpha$ (mJy)$^a$ | ...                   | 0.40 ± 0.14            |
|           | $\nu_c$ (Hz)$^b$ | ...                   | (5.5 ± 1.8) $\times$ 10$^{13}$ |
|           | $\chi^2$/dof  | 6.6                    | 2.3                    |

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Notes.

$a$ The radio flux density at 5 GHz.

$b$ The energy index.

$c$ The cutoff frequency.

d The mid-infrared flux density at 22 $\mu$m.
single/double cutoff–PL modeling of the radio-to-optical spectral energy distribution. The mid-infrared spectrum with Spitzer (Werner et al. 2012) exhibits a similar trend.

The radio-to-optical spectral energy distribution from the west hot spot of Pictor A has been widely attributed to synchrotron emission from relativistic electrons accelerated via the first-order Fermi mechanism in the jet terminal shock (e.g., Meisenheimer et al. 1989, 1997; Wilson et al. 2001; Tingay et al. 2008; Werner et al. 2012). The linear polarization in the radio (Perley et al. 1997) and optical (Thomson et al. 1995) frequencies reinforces the synchrotron origin. However, the standard one-zone model, basically predicting a PL electron energy distribution with a high-energy cutoff and/or break (e.g., Carilli et al. 1991), is unable to reproduce the mid-infrared excess. Therefore, in order to interpret the mid-infrared data, a two-zone model is strongly favored.

Previously, mid-infrared properties have been investigated with Spitzer for about two dozen hot spots of the FR II radio galaxies. Stawarz et al. (2007) successfully reproduced the radio-to-X-ray spectral energy distribution of the two high-luminosity hot spots of Cygnus A, namely, A and D (Hargrave & Ryle 1974), with the one-zone synchrotron+SSC model, where the mid-infrared data agree with the high-frequency end of the synchrotron component. The mid-infrared spectrum of the radio structures associated with the hot spots of the FR II source, 3C 33, is reported to be smoothly connected to the synchrotron radio spectrum, while the second synchrotron component is suggested to interpret the X-ray spectrum for the most radio structures (Kraft et al. 2007). Werner et al. (2012) systematically studied the multi-frequency spectrum of 17 radio hot spots, from which the mid-infrared and X-ray emissions were detected, including the west hot spot of Pictor A. None of these objects are reported to show a clear sign of the mid-infrared excess. However, they utilized the radio data only at 5 GHz instead of the wide-band synchrotron radio spectrum, and their spectral model is simply based on the strong shock assumption (α = 0.5). These simplifications are possible to conceal the mid-infrared excess since the model with α = 0.5 should artificially overpredict the mid-infrared flux density when it is fitted to the 5 GHz radio data, particularly for sources with a soft radio spectrum (α > 0.5).

Actually, owing to the careful modeling of the synchrotron spectrum, the present study succeeded in detecting the mid-infrared excess from the west hot spot of Pictor A, which exhibits a relatively soft radio spectrum (α = 0.74 ± 0.015). This result is regarded as the first discovery of the mid-infrared excess from hot spots in FR II radio galaxies.

3.2. How to Constrain the Magnetic Field

In the following, the two-zone scenario is adopted to examine the physical parameters in the hot spot. The magnetic field of the main and excess components is estimated from the cutoff frequency. The cutoff frequency is usually attributed to the maximum Lorentz factor of accelerated electrons or the break Lorentz factor due to radiative cooling. The previous studies on the west hot spot of Pictor A (e.g., Tingay et al. 2008) suggests that the synchrotron cooling dominates over the inverse-Compton one. The analytical estimates by Kino & Takahara (2004) indicate that the observed spectral parameters of the object are found to be within the cooling break regime.

Figure 4. Relation between the magnetic field $B$ and the thickness of the acceleration region $R$ for a representative downstream flow velocity of $v = 0.3c$, estimated from $\nu_{\text{c}}$ under the cooling break hypothesis. The acceptable spaces to the main and excess components are indicated by the thick solid line and blue hatched area, respectively. The upper limit on $R$ was estimated from the radio emitting volume (Wilson et al. 2001). The horizontal dashed lines indicate the magnetic field strength of $B_{\text{nc}} = 360 \mu G$ and $B = 2 mG$. The vertical arrows denote the representative region sizes discussed in Section 3.3.

By equating the synchrotron cooling timescale $t_{\text{syn}} = \frac{3m_e c}{4\pi e B^2 \nu \gamma_n}$ to the adiabatic loss timescale $t_{\text{ad}} = \frac{R}{v}$, the break Lorentz factor is derived as $\gamma_n = \frac{6m_e c^2}{\pi e B^2 R}$ (e.g., Inoue & Takahara 1996), where $m_e$ is the electron rest mass, $u_B = B^2/8\pi$ is the energy density of the magnetic field $B$, $\sigma_T$ is the Thomson cross section, $R$ is the thickness of the acceleration region for electrons with $\gamma_n$, and $v$ is the downstream flow velocity in the shock frame. In this condition, the magnetic field is constrained from $\nu_{\text{c}} (\propto \gamma_n^2)$ as follows:

$$B^3 \simeq \frac{27\pi e m_e v^2 c^2}{\sigma_T^2} R^2 \nu_{\text{c}}^{-1}, \quad (2)$$

where $e$ is the electron charge.

3.3. Comparison with the Minimum-energy Magnetic Field

Figure 4 shows the acceptable parameter space on the $B$–$R$ plane, derived from Equation (2), for a representative value of the flow velocity, $v = 0.3c$ (e.g., Kino & Takahara 2004). The excess component tends to exhibit a higher magnetic field due to its lower $\nu_{\text{c}}$ value.

In order to infer the physical condition for the main component, the minimum-energy argument (Miley 1980) is adopted as the simplest working hypothesis. Adopting the radio emitting volume, which is equivalent to a sphere with a radius of 250 pc (Wilson et al. 2001; Tingay et al. 2008), the spectral energy distribution shown in Figure 3 yields the minimum-energy magnetic field as $B_{\text{nc}} = 360 \mu G$. Here, the proton energy density is assumed to be equal to the electron one. On the field strength, it is suggested that the synchrotron electrons corresponding to $\nu_{\text{c}}$ for the main component are generated within $R \sim 20–30$ pc around the shock, as shown with the upward arrow in Figure 4. The estimated size is consistent with the result from the detailed spectral modeling of this hot spot without mid-infrared data ($\leq 50$ pc; Meisenheimer et al. 1997).
The first interpretation of the excess component assumes that the two components originate in the different regions within the hot spot, but with the same magnetic field (i.e., $B_{\text{me}} = 360 \mu G$). The electron cooling timescale of the excess component ($t_{\text{syn}} \lesssim 10^7$ years) is expected to be longer by a factor of 3.6 than that of the main component, due to its lower cutoff frequency by a factor of 13. This implies that the excess electron population is older than the main one. Accordingly, the excess electrons are expected to be distributed in a wider region ($R \lesssim 100$ pc; see the right downward arrow in Figure 4) than the main ones.

The second and more attractive explanation hypothesizes that the excess is produced in a region with a stronger magnetic field. A number of theoretical studies (e.g., Lucek & Bell 2000; Inoue et al. 2009; Fraschetti 2013; Araudo et al. 2015; Ji et al. 2016) proposed that the magnetic field is amplified by plasma instabilities, turbulences, or nonlinear interactions between the field and accelerated particles. Based on these studies, the amplification by a factor of at least 4–6 is achievable (Lucek & Bell 2000). Thus, the minimum-energy field in the west hot spot of Pictor A can possibly be magnified up to $B \sim 2$ mG. In Figure 4, this field corresponds to the thickness of $R = 6$–8 pc (shown with the left downward arrow).

With the VLBA image, Tingay et al. (2008) resolved the hot spot of Pictor A into substructures with a size of $\gtrsim 10$ pc. Summed over these substructures, the radio flux density was measured as $F_\nu = 121 \pm 6$ mJy at 1.67 GHz. They interpreted that these substructures correspond to the recent shocks with a higher energy density (i.e., a stronger magnetic field) than the mean energy density over the hot spot. Interestingly, the size of the excess component is comparable to those of these substructures. In addition, the 1.67 GHz flux density of the excess component, which is estimated from the double cutoff–PL fitting as $F_\nu \sim 50$–500 mJy, agrees with that of the substructures. Therefore, it is natural to arrive at the scenario where the acceleration site of the excess component is some of these substructures with a strengthened magnetic field.

### 3.4. Relation to the Origin of the X-Ray Spectrum

The X-ray spectrum measured with *Chandra* (a photon index of $\Gamma = 2.07 \pm 0.11$; Wilson et al. 2001) is reported to be significantly steeper than the synchrotron radio one. It is widely known that this inconsistency between the radio and X-ray spectral slope makes a simple one-zone synchrotron+SSC interpretation unfeasible for the wide-band spectral energy distribution from the object. Tingay et al. (2008) proposed that fresh electrons accelerated in the recent shocks, which are traced by the VLBA substructures, produce the observed X-ray spectrum via synchrotron radiation. Their hybrid synchrotron model, where the radio and X-ray photons originate in the whole hot spot and compact regions, respectively, successfully reproduced the overall spectral energy distribution. From the model, the synchrotron peak of the compact component is expected to be located in the X-ray band. The X-ray spectral break suggested in the deep *Chandra* observation (Hardcastle et al. 2016) possibly supports this explanation.

By modifying the scenario of Tingay et al. (2008), the mid-infrared excess revealed with *WISE* and *Spitzer* suggests three different populations of synchrotron electrons in the west hot spot of Pictor A, two of which are localized in the compact substructures. Assuming the magnetic field in these compact regions is magnified up to $B = 2$ mG, as discussed in Section 3.3, the synchrotron cooling timescale of the X-ray electrons is evaluated as $t_{\text{syn}} \sim 1$ years $E_{\text{keV}}^{-0.5}$, where $E_{\text{keV}}$ is the synchrotron photon energy in units of keV. This is significantly shorter than that of the mid-infrared excess, $t_{\text{syn}} \sim 75$ years $(\nu / 5.5 \times 10^{13} \text{Hz})^{-0.5}$. Therefore, one of the plausible ideas is that among the VLBA substructures, the younger ones are the origin of the X-ray spectrum, while the mid-infrared excess is radiated from the older ones.

It is claimed that the compact structures with an amplified magnetic field are a transient feature since they rapidly expand to achieve a pressure balance with the ambient region (Tingay et al. 2008). As a result, the emission from these compact regions is expected to be variable with a short timescale. This is possibly confirmed by a series of *Chandra* observations of the west hot spot of Pictor A, in which the X-ray flux decayed by $\sim 10\%$ in a timescale of 3 months (Hardcastle et al. 2016). The variability implies that the core of the X-ray emitting region might possibly be in a sub-parsec scale. Between the *WISE* and *Spitzer* observations separated by $\gtrsim 5$ years, no significant change was indicated in the mid-infrared flux when all the photometric uncertainties are taken into consideration, including the *WISE* systematic errors ($\sigma_{\text{syn}}$ in Table 1) and the *Spitzer* ones (typically 3%; Carey et al. 2012).

### 3.5. Prospects

The striking implication from the thorough investigation into the synchrotron spectrum of the west hot spot of Pictor A is that the radio and mid-infrared spectra are of a different origin from each other, as is visualized in the bottom panel of Figure 3. If this is the case in other objects, the mid-infrared emission is inferred to dominate over the radio one in particular conditions, although what controls the relative importance between the radio and mid-infrared emission remains unclear. Currently, hot spots that are bright in the mid-infrared band and relatively weak in the radio band are not yet known. The all-sky survey data with *WISE* have a great potential to search for such “mid-infrared hot spots.”

The multi-zone interpretation presented above is expected to be reinforced by precisely measuring the synchrotron spectrum in between the radio and mid-infrared frequencies.

However, the far-infrared flux of the west hot spot of Pictor A estimated from the *WISE* result, $\sim 35$ mJy at 90 $\mu m$, is below the detection limit of previous far-infrared all-sky surveys, including the *AKARI* all-sky survey catalog (0.43 Jy at 90 $\mu m$; Yamamura et al. 2012). Future observations with the next-generation infrared observatory *Space Infrared Telescope for Cosmology and Astrophysics* (SPICA; Roelfsema et al. 2017) and ALMA are of prime importance. In addition, multi-epoch observations with the *James Webb Space Telescope* in the near future will be useful to search for mid-infrared flux variations. This will constrain the size of the region and thus reconsider the substructure explanation for the mid-infrared excess from the west hot spot of Pictor A.

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