A GHz Peaked Spectrum radio galaxy born at one-tenth the current age of the Universe

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ABSTRACT
Studies of high redshift radio galaxies can shed light on the activity of active galactic nuclei (AGN) in massive elliptical galaxies, and on the assembly and evolution of galaxy clusters in the Universe. The vast majority of observed high redshift ($z > 4.5$) AGN are quasars, with very few galaxies. J1606+3124 is a radio galaxy at a redshift of 4.56, at an era of one-tenth of the current age of the Universe. Very long baseline interferometry (VLBI) images reveal a two-sided jet structure with edge-brightened terminal hotspots separated by about 68 parsecs. No evidence for the presence of extended emission (relic of past activity) is found, suggesting that it might be a nascent radio source. We study the radio properties of J1606+3124 including radio spectrum, variability, core brightness temperature, jet proper motion. All observations consistently indicate that it is a GHz Peaked Spectrum (GPS) source, making it the highest redshift GPS galaxy known to date. The expansion velocity of the hotspots and the turnover in the radio spectrum suggest that J1606+3124 is a young (kinematic age of $\sim$3000 years) and developing radio source. Its ultra-high jet power gives it a good chance to grow into a large-scale double-lobe radio galaxy. Infrared observations reveal a gas- and dust-rich host galaxy environment, which may hinder the jet growth.

Key words: galaxies: high-redshift–galaxies: active–galaxies: jets–galaxies: nuclei–proper motions – instrumentation: high angular resolution

1 INTRODUCTION
High redshift radio galaxies (HzRGs) are the progenitors of the dominant elliptical galaxies in galaxy clusters in the local Universe, and clusters are the building blocks of the Universe (Miley & De Breuck 2008). The study of HzRGs sheds light on the assembly and evolution of large-scale structures in the Universe. Moreover, HzRGs are also among the most massive galaxies at their redshifts (Overzier et al. 2009). They are therefore fascinating objects on their own to study the activity of the active galactic nuclei (AGN) and the accretion of supermassive black holes (SMBHs). However, the challenges of observing HzRGs are significant, resulting in only a few have been observed at $z \geq 4.5$, when the Universe was about one-tenth its current age (Saxena et al. 2018). Despite the observational difficulties, an in-depth study of the few individual HzRGs that have been identified and confirmed is well worthwhile and necessary due to the critical value of the HzRGs in astrophysical research.

The source FIRST J160613.1+312623 (in short, J1606+3124) is a radio galaxy at $z = 4.56$ (Malkin 2018). It is very faint in the optical band (Stanghellini et al. 1993) but bright in the infrared (named WISEA J160608.53+312446.5, Cutri et al. 2013) and radio bands (e.g., Owen & Mushotzky 1977). J1606+3124 has been detected in several radio surveys, including the Green Bank 91 m telescope survey at 4.85 GHz (Gregory & Condon 1991; Becker et al. 1991), the Faint Images of the Radio Sky at Twenty Centimeters (FIRST, Becker et al. 1995) of the Very Large Array (VLA) and NRAO VLA Sky Survey at 1.4 GHz (NVSS, Condon et al. 1998), the VLBA Calibrator Survey (VCS, Beasley et al. 2002) and the Combined Radio All-Sky Targeted Eight GHz Survey of the VLA at 8.4 GHz (CRATES, Healey et al. 2007). It has also been detected in the ongoing surveys, such as the Very Large Array Sky Survey at 3 GHz (VLASS, Gordon et al. 2020) and the Australian Square Kilometre Array Pathfinder (ASKAP) continuum survey at 0.888 GHz (the first large-area survey named RACS, McConnell et al. 2020).

There was once a controversy in the radio classification of J1606+3124. In early observations made three decades ago, this source was identified as a gigahertz-peaked spectrum (GPS) radio source (Stanghellini et al. 1993). However, some other subsequent studies identified it as a flat spectrum source (Torniainen et al. 2018). A more recent study (Malkin 2018) confirms that J1606+3124 is a GHz Peaked Spectrum radio source. Despite the controversy, the source is still a good candidate for studying the assembly and evolution of galaxy clusters in the early Universe.

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GPS sources are classified based on the radio spectral shape, and they are a hybrid class of quasars and galaxies. There are significantly different redshift distributions between the two classes: GPS quasars are found at a wider redshift range (1 ≤ z ≤ 4) (O’Dea et al. 1991), while GPS galaxies tend to be found at relatively lower redshifts (0.1 ≤ z ≤ 1) except for only a few at z > 2 (O’Dea et al. 1996; Mingaliev et al. 2012). This difference in this redshift distribution is probably due to observational effects, i.e., quasars are more easily observed at higher redshifts than galaxies, in addition to other possible intrinsic mechanisms. J1606+3124 is at a cosmic era shortly after the end of reionization, while AGN activity peaks at z = 2 – 3 (Schmidt et al. 1995; Kauffmann & Haehnelt 2000). If J1606+3124 is indeed a GPS source, then it is an important target for studying how AGN activity is triggered during the important transitional phase towards its peak of activity.

In addition to the convex spectrum shape, the observed characteristics of GPS radio sources also include high radio luminosity, small size (<1 kpc), low-amplitude variability on time scales from hours to decades, and low radio polarisation fractions (O’Dea 1998). More evidence for GPS identification can be obtained by studying the radio structure on parsec (pc) scales.

To further clarify the radio nature of J1606+3124 and study its radio properties, we collected interferometric data of J1606+3124 at multiple frequencies with different resolutions, obtained maps of the jet structure and spectral index distribution on milli-arcsec (mas) scales, measured the advancing velocity of the hotspots, and analysed the variability and radio spectrum of the whole source to verify it as a GPS galaxy from multiple perspectives. Throughout this paper, we adopt a flat $\Omega = \Omega_0 = \Lambda$ cosmological model with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_M = 0.73$, and $\Omega_\Lambda = 0.27$. In this model, 1 mas angular size corresponds to 6.789 pc projected linear size at the source redshift $z = 1.56$ (Malkin 2018). A proper motion speed of 1 mas yr$^{-1}$ corresponds to 123 c.

2 DATA AND METHODS

VLBI data from five epochs were used for the study in this paper, see Table 1 for observational details. Four epochs were obtained from the Astrogate VLBI database. This database is mainly used for geodesy and astrometry studies (e.g., Beasley et al. 2002). Most of these observations were made in the snapshot mode at 2 and 8 GHz dual frequencies. The phase of the visibility data has been calibrated, so we only need to import the downloaded data into the Difmap software package (Shepherd 1997) for self-calibration and imaging. Another epoch of data was observed with the Very Long Baseline Array (VLBA) at 8.4 GHz on March 19, 2017 among a project (code: BZ064) of studying the jet structure and proper motion of a high-redshift AGN sample. The VLBA observation and data processing are described elsewhere (Zhang et al. in prep.). In this paper, the calibrated data are used directly for further analysis. We performed mapping with natural weights and obtained the highest resolutions of 0.8 mas$^2$ at 8.4 GHz and 3.7 mas at 2.3 GHz, respectively. The data on March 19, 2017 had the longest integration time and the broadest bandwidth, and obtained the lowest image noise of 0.1 mJy beam$^{-1}$.

To quantitatively describe the physical properties of the J1606+3124 jet, we fit its emission structure with a number of Gaussian models (Table 2). Based on the experience of processing VLBI survey data, the uncertainty of the flux density is about 5 per cent. The uncertainty of the astrometry of J1606+3124 is 0.16 mas. The jet kinematics analysis in this paper is related to the change of the relative position of jet components, not the absolute position. Therefore the uncertainty of the absolute astrometry does not affect the jet kinematics. The position error of the jet component is mainly determined by the image signal-to-noise ratio and the size of the synthesised beam. We estimated the errors of jet component size and distance following the formula given in Fomalont (1999).

In addition to the above image data, we collected data points of J1606+3124 from the NASA/IPAC Extragalactic Database (NED) and from the RATAN-600 radio telescope (Mingaliev et al. 2012) to construct the radio spectrum, which is shown in Figure 4.

This source has been monitored by the 40-metre radio telescope of the Owens Valley Radio Observatory (OVRO) at 15 GHz (Richards et al. 2011). The radio lightcurve is used for variability analysis.

3 RESULTS

3.1 Radio morphology

J1606+3124 is unresolved in the arcsec-resolution images obtained from the VLA/VLASS (resolution of 2.5 arcsec), VLA/FIRST (5 arcsec), ASKAP/RACS (15 arcsec) and VLA/NVSS (45 arcsec). Figure 1 shows the compact structure of J1606+3124 revealed in the VLA/FIRST and ASKAP/RACS images.

The source is resolved into two components along the north-south direction in the 5-GHz VLBA images at mas scales (Helm-Boldt et al. 2007). These two components show similar morphology and their emission peaks are separated by ~8 mas, reminiscent of a Compact Symmetric Object (CSO, Owsianik & Conway 1998; O’Dea & Saikia 2021). The 5-GHz VLBA observation was made in 2006 January. Since the source does not have prominent variability (Section 3.3), we can compare the VLBI flux density with the total flux density measured by RATAN-600 at the same frequency in 2006 October, and find that 94 per cent of the radio emission comes from the mas-scale structure revealed by the VLBI image.

Our new VLBA image is shown in Figure 2. It was observed at 8.4 GHz, with a higher resolution of 2.5 mas × 0.8 mas than that of the 5-GHz image, enabling to reveal finer structure. Except for two edge-brightened components labelled as N1 and S1, two other components (N2 and S2) are identified in the intervening region. N2 is located midway between N1 and S1, and S2 is closer to S1. The four components are aligned in the northwest-southeast direction, at a position angle of ~17°.

At all three frequencies (2, 5 and 8 GHz), S1 is the brightest component in the VLBI images (Table 2) and is more compact than N1. The spectral indices of S1 and N1 are calculated from model fitting results at 2 GHz and 8 GHz, which are −0.68 and −0.94, respectively. N2 and S2 are only identifiable at 8.4 GHz. To

1 Astrogate database maintained by L. Petrov: http://astrogate.org/.

2 1 mas corresponds to a projected size of ~6.8 pc.
investigate their spectral indices, we produced spectral index maps using the 2 and 8 GHz VLBI data. We first created two images with the same map size and pixel size and restored the 8-GHz image with the 2-GHz beam shape, then calculated the frequency-dependent opacity (Kim & Trippe 2014). Next, we used the calculated offset to translate the 8-GHz image and to align with the 2-GHz image. Finally, the spectral index was calculated for each pixel, and the resulting dataset was plotted as the spectral index map. Figure 3 shows the spectral index map derived from the 2018 epoch data. Spectral index maps in the other epochs look similar, so we do not repeat the display here. Figure 3 clearly shows that the spectrum is flattened toward the southern terminal of the radio structure, while the centroid of the southern component (i.e., the location of S1) is not the flattest but shows a spectral index between ~0.4 and ~0.5, a value between the optically thin and optically thick regimes. The spectral indices of N1 and S1 inferred from Fig. 3 are consistent with those calculated directly from the model fitting results. The spectral indices of N1 and S1 are 0.3 and 0.2, respectively. The derived brightness temperatures are listed in Table 3.

None of the VLBI components satisfy the conventional definition of a flat-spectrum radio core. Instead, a more natural interpretation is that they are hotspots in the jets.

The brightness temperatures of the components can be calculated from the VLBI observables, including the flux density and size (Kovalev et al. 2005). The derived brightness temperatures are listed in the last column of Table 2. S1 has the highest brightness tempera-

### Table 1. Information about the VLBI observations of J1606+3124

| Code   | Date       | Frequency (GHz) | Bandwidth (MHz) | Bmaj (mas) | Bmin (mas) | BPA (°) | Peak (mJy beam⁻¹) | σrms (mJy beam⁻¹) | Ref. |
|--------|------------|-----------------|-----------------|------------|------------|---------|------------------|------------------|-----|
| BB023  | 1996-05-15 | 2.3             | 9.0             | 3.7        | 20.8       | 839.0   | 1.0              | 1                | 1   |
| ...    | ...        | ...             | ...             | ...        | ...        | ...     | ...              | ...              | ... |
| bg219e | 2014-08-09 | 2.3             | 8.2             | 4.3        | 18.8       | 737.0   | 1.3              | 1                | 2   |
| ...    | ...        | ...             | ...             | ...        | ...        | ...     | ...              | ...              | ... |
| BZ064B | 2017-03-19 | 8.4             | 512             | 2.5        | 0.8        | 979.7   | 0.1              | 1                | 2   |
| ...    | ...        | ...             | ...             | ...        | ...        | ...     | ...              | ...              | ... |
| ug002d | 2018-03-26 | 2.3             | 96              | 6.6        | 4.1        | 685.9   | 0.9              | 1                | 1   |
| ...    | ...        | ...             | ...             | ...        | ...        | ...     | ...              | ...              | ... |

Notes: Col. 1 – project code; Col. 2 – observation date; Col. 3 – observing frequency; Col. 4 – bandwidth; Col. 5 – main and minor axes of the synthesized beam (full width at half-maximum, FWHM) and the position angle of the major axis, measured from north to east; Col. 8 – peak intensity in the image; Col. 9 – root mean square (rms) noise in the image; Col. 10 – reference to the corresponding VLBI experiment: 1–Astrogeo database; 2–this paper.

### Table 2. Model-fitting parameters of the VLBI components.

| Epoch (YYYY-MM-DD) | Comp. | S_peak (mJy beam⁻¹) | S_maj (mJy) | R (mas) | P.A. (°) | D_comp (mas) | εp (mas) | T_b (×10⁴ K) |
|--------------------|-------|---------------------|-------------|---------|---------|-------------|----------|-------------|
| Col. 1             | Col. 2 | Col. 3              | Col. 4      | Col. 5  | Col. 6  | Col. 7      | Col. 8    | Col. 9       |
| 1996-05-15         | S1    | 302±15              | 366±18.9    | ...     | 0.56   | 0.01       | 11.3±0.7 |             |
|                    | N2    | 74.4±4.2            | 73.9±4.5    | 2.47±0.03 | 19.9±0.3 | 0.39       | 4.8±0.7  |             |
|                    | N1    | 32.8±2.1            | 46.2±3.2    | 7.98±0.05 | 17.3±0.2 | 0.76       | 0.78±0.1 |             |
| 2014-08-09         | C     | 334±17              | 373±18.9    | 0.0±0.90 | 0.50   | 0.01       | 13.6±0.8 |             |
|                    | S2    | 115±6               | 29.6±2.2    | 1.17±0.02 | 14.1±0.5 | 0.17       | 9.5±1.9  |             |
|                    | N2    | 68.4±3.8            | 80.6±4.7    | 2.66±0.03 | 17.8±0.3 | 0.63       | 1.8±0.2  |             |
|                    | N1    | 26.9±1.5            | 36.7±2.1    | 8.29±0.04 | 16.3±0.1 | 0.82       | 0.49±0.4 |             |
| 2017-03-19         | C     | 319±16              | 352±17.7    | ...     | 0.0±0.90 | 0.42       | 19.4±1.1 |             |
|                    | S2    | 120±6               | 25.9±1.8    | 1.00±0.01 | 22.5±0.3 | 0.13       | 15.3±2.6 |             |
|                    | N2    | 70.7±3.9            | 85.2±5.0    | 2.70±0.03 | 17.5±0.3 | 0.56       | 2.6±0.3  |             |
|                    | N1    | 26.7±2.1            | 36.8±3.3    | 8.28±0.08 | 16.2±0.3 | 0.74       | 0.66±0.13|             |
| 2017-09-18         | C     | 324±17              | 327±17.3    | ...     | 0.0±0.90 | 0.49       | 12.2±1.2 |             |
|                    | N2    | 139±8               | 99.8±6.8    | 2.49±0.06 | 14.4±0.7 | 0.76       | 1.6±0.2  |             |
|                    | N1    | 27.8±1.6            | 34.9±2.2    | 8.09±0.07 | 16.0±0.2 | 1.11       | 0.25±0.1 |             |
| 2018-03-26         | C     | 269±14              | 289±14.8    | ...     | 0.4±0.01 | 13.5±0.8  |           |             |
|                    | S2    | 125±6               | 23.2±1.8    | 1.07±0.02 | 3.5±0.5  | 0.14       | 11.2±2.0 |             |
|                    | N2    | 69.4±4.0            | 79.5±5.0    | 2.63±0.04 | 16.7±0.4 | 0.54       | 2.3±0.3  |             |
|                    | N1    | 27.2±1.7            | 34.2±2.3    | 8.24±0.05 | 16.1±0.2 | 0.69       | 0.64±0.08|             |

Notes: Col. 1 – observing date; Col. 2 – identifier of the fitted model component; Col. 3 – peak intensity; Col. 4 – total flux density; Col. 5 – angular separation of the component with respect to E0; Col. 6 – position angle of the component with respect to E0, measured from north to east; Col. 7 – fitted FWHM size of the circular Gaussian model component; Col. 8 – uncertainty of D_comp; Col. 9 – brightness temperature.

*The size of the component was too small to be fitted with a Gaussian, the minimum resolvable size is used as an upper limit (see Kovalev et al. 2005).
Figure 1. Arcsec-scale images of J1606+3124. Top: FIRST image at 1.4 GHz. The resolution is 5". Bottom: ASKAP RACS image at 888 MHz. The resolution is 27.1". The lowest contour in the image represents 3 times the rms noise, and the contours increase in steps of 2. The color scale represents the brightness in logarithmic scale.

Figure 2. VLBA image of J1606+3124 at 8.4 GHz. The observation was made on 2017 March 19. The image parameters are referred to Table 1.

Figure 3. Spectral index map of J1606+3124. It is created from the simultaneous dual-frequency 2.3/8.4 GHz VLBI data on epoch 2018 March 26. The spectral indices of components S1, N2, N1 are $-0.4$, $-0.6$ and $-0.8$, respectively.

3.2 Spectrum

The radio spectrum of the entire source is shown in Figure 4. The data shown as solid circles were collected from the RATAN-600 observations (Mingaliev et al. 2012) observed in five epochs from 2006 October to 2010 May, and different epochs were distinguished by different colours. The simultaneous RATAN-600 observations at six frequencies show a peaked spectrum with a turnover at a few GHz, which can be fitted with a function that describes self-absorbed synchrotron radiation emitted by electrons with a power-law energy distribution in a homogeneous magnetic field (Pacholczyk 1970; Tüller et al. 1999):

$$F_\nu = F_m \left(\frac{\nu}{\nu_m}\right)^{\alpha_{thick}} \frac{1 - \exp(-\tau_m (\nu / \nu_m)^{\alpha - \alpha_{thick}})}{1 - \exp(-\tau_m)} ,$$

where $\nu_m$ is the turnover frequency; $F_m$ is the maximum flux density at the turnover frequency; $\alpha$ and $\alpha_{thick}$ describe the spectral indices of the optically thin and thick parts of the spectrum, respectively; $\tau_m$ can be approximated as the optical depth at the turnover. Because RATAN-600 observations lack data below 1 GHz, the absorbed section of the spectrum can not be well constrained. Therefore, we fixed $\alpha_{thick} = 2.5$ in the fitting, the theoretical value of synchrotron self-absorption (SSA). The fitted turnover frequency falls between 1.9 and 3.2 GHz. After fitting 5000 iterations of the spectrum constructed by averaging each individual-frequency data in
all epochs from Mingaliev et al. (2012), the best-fit parameters are $F_m = 977 \pm 41$ mJy, $\nu_m = 2.2 \pm 0.1$ GHz, $\alpha = -0.58 \pm 0.04$ and $\tau_m = 0.41$. The inset plot enlarges the spectrum around 22 GHz, showing that the observed 22-GHz flux density is lower than the fitted value.

We also collected the data points from the NED database based on their availability. Two data points obtained from the latest VLA/VLASS and ASKAP/RACS are also added to the plot. Although these observations were made at different epochs, frequencies, and resolutions, the radio spectrum still provides valuable information given that the flux density of this source is concentrated on the parsec scale (Section 3.1) and has no significant variability (Section 3.3). As with the RATAN-600 data, the NED spectrum also shows a turnover around 1 GHz. We fit all data points from the NED and RATAN-600, and obtained the parameters: $F_m = 724 \pm 12$ mJy, $\nu_m = 1.9 \pm 0.1$ GHz, $\alpha_{\text{thick}} = 2.8 \pm 0.4$, $\alpha = -0.34 \pm 0.03$ and $\tau_m \approx 0.22$. The difference is that the peak frequency and peak flux density of RATAN-600 spectrum are higher than those of the all-data spectrum. Compared to the RATAN-600 spectra, the shape of the low-frequency section of the all-data spectrum is better fitted due to more data points at 0.33, 0.888, 1, and 1.4 GHz. The optically thick spectral index $\alpha_{\text{thick}} = 2.8$ is larger than $\alpha_{\text{SSA}} = 2.5$ of the synchrotron self-absorption spectrum, likely due to that the low-frequency absorption spectrum results from a mixture of SSA and free-free absorption (FFA). Future observational studies of the content and distribution of ionised gas in J1606+3124 will help to determine whether the host galaxy contains significant amounts of ionised gas that is responsible for the FFA and spatially correlated with the jet, and whether the gas ionisation results from the jet-ISM interactions. The latter point can also be explored from VLBI polarimetric observations if the collisions between the jet and massive clouds occur at the terminal hotspots or internal hotspots (An et al. 2020). The optically thin part of the NED spectrum is not very steep, suggesting that fresh relativistic electrons are continuously injected into the jets and radio lobes from the central AGN. This also implies that the radio structure is in its early evolutionary stage and is still growing (see also the same conclusion from the jet proper motion analysis in Section 3.4).

The fitted turnover frequency corresponds to 10.6–17.8 GHz in the source rest frame, classifying J1606+3124 as a high frequency peaker (HFP, Dallacasa et al. 2000), the youngest sub-group in GPS sources (Dallacasa 2003).

Another interesting feature in Figure 4 is that there is a drop between 22 and 90 GHz (122 and 500 GHz in the source rest frame, respectively). The same phenomenon is observed in the RATAN-only spectra (see discussion above). Such a millimetre-wavelength break in the optically thin part of the synchrotron spectrum is also known as spectral ageing due to the energy-dependent loss rate of synchrotron-emitting electrons. In the high-redshift Universe, the cosmic microwave background (CMB) energy density increases with $(1+z)^4$, causing that the relativistic electrons cool preferentially by scattering off CMB photons, rather than by synchrotron emission loss (Ghisellini et al. 2014). In addition to the observed break in the radio spectrum at millimetre wavelengths, another effect of the enhanced inverse Compton loss is that it can lead to the extended radio structure failure to be detected at GHz frequencies. This could be an explanation of the absence of large-scale extended jet in HzRG images.

However, we should note that the low-frequency spectrum is constrained by only two data points, which were observed by ASKAP at 888 MHz and by Westerbork at 330 MHz, and the difference in observation time between these two data points is very long. Observing more data points below 1 GHz using the LOw Frequency ARray (LOFAR) and uGMRT can help to accurately limit the low-frequency spectral shape. Similarly, there is only one data point at the high-frequency end, resulting in less stringent limits on synchrotron ageing. The addition of J1606+3124 observations at 22–90 GHz is critical for estimating the spectral age.

### 3.3 Variability

Figure 5 shows the lightcurve of J1606+3124. Except for two gaps from epoch 2008.6 to epoch 2009.2 and from 2019.6 to 2020, the monitoring program continuously covers the period from 2008.0 to 2020.9. The average time interval between two adjacent observations is approximately six days. Some bad data points that deviate significantly from the mean value or show large measurement errors were discarded.

We used the modulation index $V$ to characterise the variability in the lightcurve (Murphy et al. 2021).

$$V = \frac{1}{S} \sqrt{\frac{N}{N-1} \left( \frac{S^2}{N} - \overline{S^2} \right)} ,$$

$$\eta = \frac{N}{N-1} \left( \frac{S^2}{\overline{S^2}} - \frac{\overline{S^2}}{\overline{S^2}} \right) ,$$

where $N$ is the number of data points, $S$ is the flux density, $\overline{S}$ is the mean of $S$, $\overline{S^2}$ is the weight of the ith data point denoted by $w_i = 1/\sigma_i^2$, $\sigma_i$ is the measurement uncertainty, and $\eta$ is a measure of the statistical significance of the variability. The statistical significance of variability is described by the parameter $\eta$. In Murphy et al.

| $\nu$ (GHz) | telescope | $S$ (mJy) | ref. |
|------------|-----------|-----------|-----|
| 90.0       | NRAO11m   | 130±70    | 1   |
| 22.0       | KVN       | 380±80    | 2   |
| 21.7       | RATAN-600 | 262±33    | 3   |
| 15.0       | OVRO      | 428       | 4   |
| 11.2       | RATAN-600 | 507±28    | 3   |
| 8.4        | VLA       | 486.8     | 5   |
| 7.7        | RATAN-600 | 627±43    | 3   |
| 5.0        | VLA       | 600±30    | 6   |
| 5.0        | VLBA      | 738.1     | 7   |
| 4.85       | GBT91m    | 444±67    | 8   |
| 4.85       | GBT91m    | 453±40    | 9   |
| 4.85       | GBT91m    | 393±51    | 10  |
| 4.83       | GBT91m    | 638       | 11  |
| 4.8        | RATAN-600 | 796±39    | 3   |
| 3.0        | VLA/VLASS | 637±4     | 12  |
| 2.3        | RATAN-600 | 824±63    | 3   |
| 1.4        | VLAINVSS  | 663±20    | 13  |
| 1.2        | VLA/FIRST | 649±32    | 14  |
| 1.0        | RATAN-600 | 418±32    | 3   |
| 0.888      | ASKAP/RACS| 502±15    | 15  |
| 0.33       | Westerbork | 25±4      | 16  |

References: 1 – Owen & Mulson (1977); 2 – Lee et al. (2017); 3 – Mingaliev et al. (2012) (Here, average values of all epochs are provided.); 4 – Richards et al. (2014); 5 – Healey et al. (2007); 6 – Owen et al. (1978); 7 – Helmboldt et al. (2007); 8 – Becker et al. (1991); 9 – Gregory et al. (1996); 10 – Gregory & Condon (1991); 11 – Langston et al. (1990); 12 – Gordon et al. (2020); 13 – Condon et al. (1998); 14 – Becker et al. (1995); 15 – McConnell et al. (2020); 16 – Rengelink et al. (1997).
Figure 4. Radio spectrum of J1606+3124. Black data points are obtained from NED (see details in Table 3) and other coloured data points come from different epochs of RATAN–600 radio telescope’s observations. The green, blue, orange, red and purple lines respectively are SSA model fitting with green, blue, orange, red and purple data points under the conditions of $\alpha_{\text{thick}} = 2.5$, more discussion in Section 4. But the black curve line was SSA model fitting with all the data points, including black data points and other coloured data points.

3.4 Proper motion

As the radio core was not detected in the VLBI image, we turned to calculate the expansion velocity of the jet component with respect to the brightest terminal hotspot S1. Figure 6 shows the change of the relative distance with time. The forth epoch data on 2017 September 18 has a larger synthesised beam than other epochs (Table 1) due to its different $(u,v)$ coverage from other epochs, resulting in that the S2 component is mixed in S1. That leads to a systematic offset of N2 and N1 toward the north. Therefore we didn’t use the forth epoch data in the proper motion calculation. S2 was detected only in three epochs separated by ~3.5 years (0.6 year in the source rest frame), which is too short to produce a reliable proper motion result. Therefore, we only calculated the expansion rates of N2 and N1. Using a linear regression fit, we obtained the relative proper motions, $\mu_{N1} = 0.014 \pm 0.003$ mas yr$^{-1}$ and $\mu_{N2} = 0.010 \pm 0.002$ mas yr$^{-1}$, corresponding to apparent transverse speeds of $1.72 \pm 0.37$ $c$ (N1), $1.23 \pm 0.25$ $c$ (N2). These two velocities are consistent within 2$\sigma$. If we adopt the simplest assumption that the velocities of the jets knots and hotspots on both sides are equal and remain constant, then we can estimate the advancing velocity of the hotspot to be 0.86 $c$, suggesting a moderately relativistic jet flow. The derived jet proper motions of J1606+3124 are significantly lower than those of the high-redshift blazars in previous studies (Veres et al. 2010; Frey et al. 2015; Perger et al. 2018; Zhang et al. 2020; An et al. 2020).

N1 and N2 have positive proper motions, indicating that they are moving away from S1. Although we did not calculate the proper motion velocity of S2, we can see from the model fitting results that S2’s position in the epochs 2017 and 2018 is closer to S1 than that in 2014. This shows that S2 is moving toward S1 and further suggests that the radio core is located in the region between S2 and N2. If this is the case, the morphology can be naturally explained as a CSO with the longer northern jet moving towards the observer. The central core is not prominent, which is common in CSO galaxies (Peck & Taylor 2000).
We find that the brightness of the terminal hotspots N1 and S1 is not symmetric. This asymmetric brightness obviously cannot be explained by the Doppler beaming effect, since the beaming effect would make the advancing jet brighter, however this is contradicted by the fact that the southern (receding) jet is much shorter but brighter than the northern (advancing) jet. A more likely explanation is that the two-sided jets encounter different interstellar medium (ISM) environments, with the southern jet encountering a more dense medium and more intense jet-ISM interactions. This reflects the complexity of the AGN host galaxy environment. The study of more high-redshift AGN will help determine whether this asymmetry or inhomogeneity is more pronounced and more common in the high-redshift AGN.

There are two widely discussed models for the interpretation of the compact radio structure of GPS sources. The ‘youth’ model (e.g., Phillips & Mutel 1982) considers the GPS sources to be only \(10^{3–5}\) years old and at a very early stage of radio source evolution (An & Baan 2012), compared to the typical ages of \(10^{7–8}\) years for large-scale classical double-lobe galaxies. The ‘frustration’ model suggests that the host galactic environment of GPS sources severely limits the development of its jets, causing them to fail to grow and be confined to sub-kpc scale (e.g., van Breugel et al. 1984; O’Dea et al. 1991). Measuring the age of a GPS source is a straightforward way to resolve the above controversy. The kinematic age can be derived by measuring the ratio of the angular distance between two terminal hotspots to the separation velocity. Adopting the simplified assumption, i.e., assuming that the hotspots expand at the same rate at both sides and a constant rate, we can estimate the jet ejection time to be around epoch 1420, which corresponds to a kinematic age of \(~3300\) years in the source rest frame. This gives support to the notion that J1606+3124 is a young radio source.

Assuming that the core is located in the middle of N2 and S2, we may estimate the length ratio of the advancing and receding jets to be \(\sim 3.37\), from which we may further estimate \(\beta \sin \theta = 0.542\), where \(\beta\) is the jet speed in the unit of \(c\), \(\theta\) is the viewing angle between the jet direction and the line of sight. The jet proper motion can be described as \(\beta_{\text{app}} = \beta \sin \theta / (1 – \beta \cos \theta)\). The jet proper motion speed is in the range of 0.61\(c\) and 0.86\(c\). Putting these two speeds into the equations, we obtained the viewing angle in the range of \(56°–78°\). The jet speed ranges from 0.55\(c\) to 0.66\(c\), consistent with the average value of hotspot advancing velocities in high-power CSOs (An & Baan 2012).

### 4 DISCUSSION

High-redshift AGN, especially those near the end of the cosmic reionisation, have received significant attention because they provide strong constraints on the growth of the earliest SMBHs (Volonteri 2010). Observations of high-redshift quasars \((z > 6)\) indicate that SMBHs with masses greater than \(\sim 10^9 M_\odot\) formed within the first billion years after the Big Bang (Mortlock et al. 2011; Wu et al. 2015; Bahados et al. 2018).

However, the search for high-\(z\) AGN poses some technical challenges, mainly the difficulty of obtaining the spectroscopic redshifts of high-\(z\) objects. On the other hand, in the host galaxies of high-\(z\) AGN, large amounts of gas and dust obscure the emission from the central AGN, increasing the difficulty of detection. Dust-obscured AGN shows an excess of mid-infrared emission at longer wavelengths, due to the emission from the heated dust present in the line of sight. Indeed, the average spectral energy distribution of obscured quasars is known to show a steeper rise with the wavelength compared to unobscured quasars (e.g. Mullaney et al. 2011), implying that obscured AGN would have relatively redder mid-infrared colours. By cross-matching the Sloan Digital Sky Survey (SDSS) and NASA’s Wide-field Infrared Survey Explorer (WISE) catalogues, Hickox et al. (2017) found that a WISE colour of \(W2 – W3 = 3.3\) mag clearly separates the obscured AGN from the unobscured ones. The WISE colours \(W2 – W3\) and \(W1 – W2\) of J1606+3124 are 3.81 mag and 0.37 mag, respectively (Cutri et al. 2013), clearly classifying it as a dust-obscured source. Most dust-obscured high-redshift infrared AGN are found to be radio weak, such as WISE J224607.56–052634.9 \((z = 4.6\), Fan et al. 2020) and COS–87259 \((z = 6.8\), Endsley et al. 2021), whose radio emission is a mixture of weak jet, quasar-driven winds, and star formation.
activity (Gabányi et al. 2021; Richards et al. 2021). High-redshift galaxies with extremely high-power jets like J1606+3124 are rare.

Radio waves are not obscured by dust and can be used to detect the nuclear regions of distant AGN. High-resolution radio interferometers are capable of imaging radio structures with sub-second to mas resolutions. Moreover, radio jets are directly associated with AGN activity and are crucial for studying AGN phenomena and the feedback of the jets to their host galaxies (Blandford et al. 2019).

Over the last two decades, large optical and infrared observation campaigns have continuously expanded the size of the high-$z$ AGN sample (Inayoshi et al. 2020, and references therein). More than 250 quasars have been found at $z > 5.7$ (e.g., Baiada et al. 2016; Jiang et al. 2016; Matsuoka et al. 2018). The radio emission is expected to be detected from early AGN (Haiman et al. 2004; Wilman et al. 2008), although their characteristics are still very uncertain. Radio-loud AGNs make up less than 10 per cent the entire AGN population (Ivezić et al. 2002) and the fraction of radio-loud fraction in the discovered high-redshift AGN is also less than 10 per cent (Yang et al. 2016). However whether the radio-loud evolution develops with redshift remains controversial (Jiang et al. 2007; Baiada et al. 2015), and whether the physical properties of high-redshift AGN are generally similar to those of low-redshift AGN remains an open question. The majority of discovered high-$z$ AGN are quasars, whereas galaxies are relatively rare (van Breugel et al. 1999; Saxena et al. 2018), mainly because these misaligned objects (galaxies) are even more challenging to observe in flux density-limited surveys.

J1606+3124 is a powerful radio galaxy formed at about one tenth of the current age of the Universe and is an excellent template for studying how the earliest-generation AGN were excited and whether the radio emission properties of early AGN are similar to those of radio sources in the local Universe. With a radio luminosity of $\sim 1.5 \times 10^{29}$ W Hz$^{-1}$, J1606+3124 is among the highest luminosity family of all radio sources (van Breugel et al. 1999; Saxena et al. 2018). Current surveys of distant objects can only detect unusually bright AGN and massive BHs that accrete near the Eddington limit (reviewed by Milei & De Breuck 2008). The presence of such extreme objects is crucial to improving our understanding of BHs and galaxy formation in the early universe.

All radio observations, including morphology, radio spectrum, variability, and jet proper motion, are consistent in indicating that J1606+3124 is a young radio galaxy.

The projected size of J1606+3124 is only 56 pc (the de-projected size $\leq 68$ pc), and it is located at the beginning of the high-power-jet sequence in the Power-Size (P-D) diagram describing the dynamical evolution of the extragalactic radio sources (O’Dea & Baum 1997; Kunert-Bajraszewska et al. 2010; An & Baan 2012). In the ‘radio power-hotspot velocity’ diagram shown in Figure 4 of An & Baan (2012), J1606+3124 belongs to a group with the high radio power and high hotspot advancing velocity, which indicates that the total jet power of J1606+3124 is intrinsically very high, making it stand out in the cosmic era at $z = 4.56$. If the central AGN can remain active for a sufficiently long time, the source has a good chance to grow into an Fanaroff-Riley type II (FRII) galaxy (Fanaroff & Riley 1974) with two extended lobes. It is worth noting that the number of extended FRII radio galaxies with redshifts above 4 detected in the radio surveys is very small. One possible reason for this is that the relativistic electrons in the high-$z$ extended radio jets or lobes are likely to lose a significant amount of energy due to the inverse Compton scattering of CMB photons, resulting in their low brightness that cannot be detected by current radio telescopes (Ghisellini et al. 2014). These factors would make that a significant fraction of HzRGs are young GPS sources (Falcke et al. 2004; Wilman et al. 2008; Saxena et al. 2017). Whereas most other large-scale HzRGs may also appear to be GPS or CSS sources because their outer extended structures are not visible, and only the active sub-kpc structure is detectable at GHz frequencies. Low frequency (e.g., below 300 MHz) radio interferometers have the potential to recover these “missing” extended radio galaxies at high redshifts (Ghisellini et al. 2014; Afonzo et al. 2015).

In addition to J1606+3124, another high-redshift GPS source with VLBI observations is FIRST J1427385+331241 ($z = 6.12$). Its VLBI image shows two compact components with a projected distance of $\sim 160$ pc (Frey et al. 2008), which is comparable to the linear scale of J1606+3124. The difference between the two is that FIRST J1427385+33124 is a quasar, while J1606+3124 is a galaxy at a relatively lower redshift. The similarities between the two include the double compact radio lobes and the steep overall spectrum, and both could be young radio-loud AGN ($< 10^5$ years). According to the unified scheme of AGN (Urry & Padovani 1995), flat-spectrum radio quasars belong to blazars with highly beamed relativistic jets pointing towards the observer. For each detected blazar, there must exist other $2^\text{I}$ (I is Lorentz factor) misaligned AGN similar with J1606+3124 and FIRST J1427385+331241 (Frey et al. 2008). However, the observed number of radio-quiet AGN is much lower than predicted. This contradiction remains an open question.

The cosmic star formation rate (SFR) density is found to evolve with redshift, peaking at $z \approx 1.5 - 2.5$ (e.g., Hopkins & Beacom 2006; Madau & Dickinson 2014). The availability of cold neutral gas in galaxies is clearly important for the formation of self-gravitating clouds of dense molecular gas. Understanding the content and distribution of neutral hydrogen in galaxies located before the SFR peak epoch is crucial for understanding the mechanisms driving the evolution of SFR density over the cosmic time (Curran 2018). It is known that in the sample of compact GPS and compact steep spectrum (CSS) radio sources, the detected fraction of AGN-associated HI 21-cm absorption is relatively higher, $\geq 30\%$, in comparison to sources with extended radio morphology (e.g. Gupta et al. 2006; Aditya & Kanekar 2018). The higher detection fraction in compact radio sources (with sizes $\leq 1$kpc) is arguably attributed to a higher gas covering factor against the background source, leading to higher absorption strength and detectability (e.g. Curran et al. 2013). However, Bicknell et al. (1997) predicted that the host galaxies of compact and young AGNs indeed harbour gas-rich medium, with a high total cold gas mass that is in the range of $10^{10} - 10^{11} M_\odot$. The fact that J1606+3124 is classified as a GPS source, and that its WISE colour properties imply dust-obscuration, indicates that this young AGN is embedded in a dust- and gas-rich ambient medium. The radio spectrum of J1606+3124 shows that ionised gas within the sub-kpc scale in the host galaxy may contribute to the low-frequency spectral turnover. If this feature is further confirmed, the study of the physical properties of the ionised gas within the narrow line region of the host galaxy is essential for understanding the dynamics of the nuclear region of J1606+3124. Combined with data from other bands, it is also possible to estimate the ratio of neutral to ionised gas, which is also an important physical parameter for determining the evolution of the AGN host galaxy’s environment over the cosmological timescale.

The kinematic age derived from the hotspot expansion speed is about 3300 years. Another way to estimate the age of a synchrotron source is to derive the lifetime of synchrotron-emitting electrons (also known as the spectral age) from a truncation of the radio spectrum at millimeter wavelengths. The spectral age depends on the magnetic field strength and spectral break frequency (Machal-
of low-redshift GPS sources is observed to be on the order of 10^{-1} Gauss; the fairly low value of magnetic field strength would result in a spectral age of a few million years for J1606+3124. In other words, if J1606+3124 is an Myr-old radio source, it should have old extended structure although it is not directly detected, and the radio structure revealed in the VLBI images could be a re-activated jet. Searching for extended emission of J1606+3124 can help clarify whether the radio structure we see on VLBI images is a primordial young source or originates from reactivation of the AGN, while the latter mechanism can limit the duty cycle of this high-\( z \) AGN (Kapinska et al. 2015). High-resolution low-frequency VLBI, such as the International LOFAR Telescope (ILT) (Sweijen et al. 2021) and the Square Kilometre Array low frequency (SKA-low) under construction, has the potential to detect the extended emission (Kapinska et al., 2015, if it is indeed present.

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