A Study of Radio Knots within Supernova Remnant Cassiopeia A

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Abstract

The study on the dynamic evolution of young supernova remnants (SNRs) is an important way to understand the density structure of the progenitor’s circumstellar medium. We have reported the acceleration or deceleration, proper motion, and brightness changes of 260 compact radio features in the second-youngest known SNR Cas A at 5 GHz based on the Very Large Array data of five epochs from 1987 to 2004. The radio expansion center is located at $\alpha(1950) = 23^h 21^m 9.7^s \pm 0.2^s$, $\delta(1950) = +58^\circ 32' 25"/2 \pm 2"/2$. Three-quarters of the compact knots are decelerating; this suggests that there are significant density fluctuations in the stellar winds of the remnant’s progenitor. We have verified that the acceleration or deceleration of compact knots is not related with the distribution of brightness. The brightening, fading, disappearing, or new appearing of compact radio features in Cas A suggests that the magnetic field in the remnant is changing rapidly.

Unified Astronomy Thesaurus concepts: Supernova remnants (1667); Proper motions (1295)

Supporting material: machine-readable table

1. Introduction

Supernova remnants (SNRs) are the result of supernova (SN) ejecta interaction with the interstellar medium (ISM). The density structure of the ISM can be revealed by the early dynamic evolution of young SNRs (Inoue et al. 2012; Sano & Fukui 2021). Cassiopeia A (Cas A; 111.7-2.1), with the expansion date estimated around 1680 CE (Ashworth 1980; Fesen et al. 2006), is the second-youngest known Galactic SNR, at a distance of $\sim 3.4$ kpc (Reed et al. 1995). The observed light echoes in Cas A suggest that this remnant came from a Type IIb SN explosion (Krause et al. 2008). With the observations from the longest radio wave to very high-energy $\gamma$-rays (Bell et al. 1975; Gotthelf et al. 2001; Morse et al. 2004; Ahnen et al. 2017), Cas A is one of the most studied objects in the sky.

Multiwavelength kinematics analysis of fragmented filaments or knots in the shock provides important information about the radiative and dynamical evolution of Cas A. Generally, bright optical knots and X-ray knots of Cas A are not consistent due to the differences of temperature and density (Patnaude & Fesen 2007) appears to be 10 times that of optical knots ($\sim 0.2$–$0.3$: Fesen et al. 2001). In radio bands, the shell of Cas A has two obvious features, a bright ring with a radius of $\sim 1.7$ pc, and a faint plateau extending to a radius of $\sim 2.5$ pc (Zirakashvili et al. 2014). The radio knots are mainly distributed in the two regions, and cover a variety of spatial scales (Tuffs 1986).

Difference in spectroscopy and velocities has divided the optical emission in Cas A into three distinct types: (1) fast-moving knots with velocities from 4000 to 6000 km s$^{-1}$ (Fesen et al. 1988; Thorstensen et al. 2001), which have strong O, Si, S, Ar, Ca emission lines but no H or He emission (Chevalier & Kirshner 1978, 1979); (2) quasi-stationary flocculi with velocities less than 500 km s$^{-1}$ (Fesen et al. 1988), which exhibit H, He, and N emission (Chevalier & Kirshner 1978, 1979); (3) fast-moving flocculi, which are the outlying faint emission knots of the remnant with velocities between 6500 and 8000 km s$^{-1}$ (Fesen et al. 1987, 1988), and have H, S, and N emission (Fesen 2001).

Supporting information
Table 1
Summary of VLA Observation for Cas A from 1987 to 2005, $\lambda = 6$ cm

| Date      | VLA Configuration | Frequencies (GHz) | Bandwidth (MHz) | On-source Time (minutes) | Observer       |
|-----------|-------------------|-------------------|-----------------|--------------------------|----------------|
| 1987.58   | A                 | 4.64, 4.97        | 3.125           | 420                      | L.Rudnick      |
| 1987.58   | A                 | 4.41, 5.08        | 3.125           | 325                      | L.Rudnick      |
| 1987.77   | A                 | 4.97, 4.41, 5.08  | 3.125           | 330                      | L.Rudnick      |
| 1987.88   | B                 | 4.97, 4.64        | 6.25            | 357                      | L.Rudnick      |
| 1987.35   | C, D              | 4.87, 4.82        | 12.5            | 53                       | L.Rudnick      |
| 1987.35   | D                 | 4.89, 4.84        | 50              | 30                       | L.Rudnick      |
| 1994.23   | A                 | 4.41, 4.49, 4.7, 5.08 | 3.125     | 545                      | L.Rudnick      |
| 1994.58   | B                 | 4.41, 4.99, 4.64, 5.08  | 12.5      | 283                      | L.Rudnick      |
| 1994.96   | C                 | 4.41, 4.99, 4.64, 5.08  | 12.5      | 182                      | L.Rudnick      |
| 1994.23   | D                 | 4.41, 4.99, 4.64, 5.08  | 12.5      | 108                      | L.Rudnick      |
| 1998.22   | A                 | 4.41, 4.99, 4.64, 5.08  | 6.25      | 453                      | L.Rudnick      |
| 1997.38   | B                 | 4.41, 4.99, 4.64, 5.08  | 12.5      | 304                      | L.Rudnick      |
| 1997.70   | C                 | 4.41, 4.99, 4.64, 5.08  | 12.5      | 182                      | L.Rudnick      |
| 1997.36   | D                 | 4.41, 4.99, 4.64, 5.08  | 12.5      | 123                      | L.Rudnick      |
| 2000.94   | A                 | 4.72, 5.0, 4.86, 4.61  | 6.25      | 537                      | L.Rudnick      |
| 2003.33   | B                 | 4.72, 5.0, 4.86, 4.61  | 12.5      | 468                      | L.Rudnick      |
| 2003.31   | C                 | 4.72, 5.0, 4.86, 4.61  | 25        | 241                      | L.Rudnick      |
| 2005.68   | D                 | 4.72, 5.0, 4.86, 4.61  | 12.5      | 183                      | L.Rudnick      |
| 2004.73   | A                 | 4.72, 5.0, 4.86, 4.61  | 6.25      | 481                      | T.Delaney      |
| 2005.35   | B                 | 4.86, 4.61, 4.72, 5.0 | 12.5      | 334                      | T.Delaney      |
| 2004.24   | C                 | 4.72, 5.0, 4.86, 4.61  | 25        | 225                      | T.Delaney      |
| 2004.62   | D                 | 4.71, 4.99, 4.86, 4.61  | 50        | 163                      | T.Delaney      |
and brightness changes of 342 compact radio features. There was no relationship between proper motion and brightness change. Anderson & Rudnick (1995; hereafter, AR95) calculated the proper motion and brightness changes of 304 radio knots using the least-squares method, which combined observations of the Cambridge 5 km Telescope and Very Large Array (VLA)\(^5\) at 5 GHz for six epochs (Cambridge 5 km Telescope: 1978, 1982; VLA: 1983, 1985, 1987, 1990). The radio emission plasma in Cas A was decelerating significantly, and the bulk expansion age was 2.5–4 times the actual age of the remnant. Brighter knots appear to be steeper spectra, and do not find the correlation between spectral index and brightness changes (Anderson & Rudnick 1996).

In this work, we report the progenitor’s circumstellar medium density distribution of Cas A by studying the motion and brightness changes of the radio emissions in the remnant. We use the VLA archival visibility observation data for Cas A at 5 GHz including five epochs of 1987, 1994, 1997, 2000, and 2004. These data were observed in the A, B, C, and D configuration of VLA, which has a high sensitivity and high resolution of 1′′5. For this paper, Section 2 describes the data used and the data calibration process, Section 3 is the calculation for the proper motion and brightness changes of compact radio peaks, and Section 4 presents the results and discussion.

2. Data Sample and Calibration

The data used in this study are the VLA archival\(^6\) C-band (5 GHz; \(\lambda = 6 \text{ cm}\)) standard-configuration data of Cas A. Each data was obtained at several frequencies around the nominal observing frequency of 5 GHz, which improves the aperture coverage. In the VLA standard configurations, the A configuration is the most diffuse, with a maximum baseline of 36.4 km and a resolution of 0′′33 in the C band; the D configuration is the most compact, with the shortest baseline of 0.035 km. The details of the data we used are summarized in Table 1, which covers five epochs of 1987.73 (Project: AB0434), 1994.75 (Project: AR0310), 1997.67 (Project: AR0378), 2000.82 (Project: AR0435), and 2004.74 (Project: AD0500),

\(^5\) https://science.nrao.edu/facilities/vla

\(^6\) https://archive.nrao.edu/archive/archiveproject.jsp

Figure 2. Position of the compact radio knots in Cas A constructed from the 1987 5 GHz observations. Contour levels in Jy beam\(^{-1}\) are 0, 0.002, 0.004, 0.006, 0.008, 0.010, 0.025, 0.05, 0.075, 0.1, 0.12, 0.15, 0.16, 0.18, 0.19, and 0.20.
| Knots | KnotAR95 | x  | y  | Box$_{x1}$ | Box$_{y1}$ | Box$_{x2}$ | Box$_{y2}$ | vx  | δvx | vy  | δvy | ax  | δax | ay  | δay | Peak Brightness | δB/kB | δδB/kB |
|-------|----------|----|----|------------|------------|------------|------------|-----|------|-----|------|-----|------|-----|------|----------------|--------|---------|
| 1     | 22       | -97.1 | -109.7 | -103.1 | -115.9 | -92.0 | -105.4 | -0.069 | 0.04 | -0.177 | 0.01 | 0.0014 | 0.0012 | 0.0026 | 0.0031 | 28.53 | 0.087 | 0.034 |
| 2     | 2        | -83.2 | -129.0 | -88.0 | -134.9 | -78.8 | -124.7 | -0.092 | 0.006 | -0.221 | 0.04 | -0.0001 | 0.0013 | 0.0021 | 0.0021 | 17.13 | 0.177 | 0.031 |
| 3     | 6        | 22.3 | -139.3 | 16.7 | -146.4 | 28.5 | -135.1 | 0.019 | 0.016 | -0.101 | 0.009 | 0.0014 | 0.0014 | 0.0002 | 0.0018 | 54.54 | 0.068 | 0.017 |
| 4     | 57.3     | -142.7 | 54.5 | -147.7 | 60.3 | -139.9 | -0.042 | 0.019 | -0.005 | 0.022 | 0.0013 | 0.0014 | -0.0038 | 0.0012 | 21.2 | 0.13 | 0.018 |
| 5     | 11       | 63.7 | -149.4 | 59.1 | -155.5 | 68.0 | -146.5 | -0.264 | 0.072 | -0.103 | 0.006 | 0.0128 | 0.0025 | 0.0006 | 0.0014 | 77.13 | 0.069 | 0.01 |
| 6     | 13       | 68.0 | -153.2 | 64.1 | -158.6 | 74.4 | -150.4 | 0.126 | 0.016 | -0.173 | 0.016 | -0.0008 | 0.0026 | 0.0022 | 0.003 | 69.28 | 0.036 | 0.01 |
| 7     | 9        | 57.5 | -127.5 | 50.8 | -133.8 | 65.5 | -121.3 | 0.137 | 0.024 | 0.042 | 0.014 | -0.0028 | 0.0016 | -0.0026 | 0.0009 | 87.47 | 0.039 | 0.011 |
| 8     | 73       | 87.0 | -111.5 | 84.1 | -116.0 | 94.6 | -105.9 | 0.312 | 0.051 | 0.001 | 0.021 | -0.0132 | 0.003 | -0.0037 | 0.0016 | 27.13 | 0.078 | 0.034 |
| 9     | 76       | 92.4 | -96.4 | 88.8 | -106.0 | 101.0 | -93.6 | 0.299 | 0.152 | -0.538 | 0.188 | -0.0227 | 0.0066 | 0.0329 | 0.0124 | 26.78 | 0.018 | 0.05 |
| 10    | 79       | 103.0 | -113.4 | 99.3 | -120.9 | 111.7 | -109.3 | 0.18 | 0.03 | -0.282 | 0.074 | -0.0007 | 0.004 | 0.0137 | 0.0028 | 22.73 | 0.019 | 0.017 |

Note. Column (1): number of each knot in this article. Column (2): number of each knot same as in AR95. Columns (3) and (4): position of compact knots in the epoch 1987 continuum map, measured in arcseconds and reference to the optical expansion center $\alpha(1950) = 23^h 21^m 11^s 9^f, \delta(1950) = +58^\circ 32^\prime 28^\prime 5$. Columns (5) to (8): box size defined for each knot, x$_1$, y$_1$, x$_2$, y$_2$ (arcseconds), reference to the radio expansion center. Column (9): $v_x$, the proper motion of each knot in R.A. (arcseconds per year). Column (10): $\delta v_x$, uncertainty in R.A. proper motion. Column (11): $v_y$, the proper motion of each knot in decl. (arcseconds per year). Column (12): $\delta v_y$, uncertainty in decl. proper motion. Column (13): $a_x$, the acceleration of each knot in R.A. (arcseconds per year squared). Column (14): $\delta a_x$, uncertainty in R.A. acceleration; Column (15): $a_y$, the acceleration of each knot in decl. (arcseconds per year squared). Column (16): $\delta a_y$, uncertainty in decl. acceleration; Column (17): peak brightness of each knot in 1987 (mJy beam$^{-1}$). Column (18): $\Delta B/kB$, annual percentage of the brightness change (percent per year). Column (19): $\delta \Delta B/kB$, uncertainty in fractional brightness change.

(This table is available in its entirety in machine-readable form.)
with a total time baseline spanning about 17 yr. In order to sample the complex spatial structure of Cas A, the aperture coverage has been maximized.

This data calibration procedure was performed by the Common Astronomy Software Applications package7 (McMullin et al. 2007). The calibrations of the primary flux density in all observing sessions are based on the 0134+329 (3C48), and the 2352+4995 is the phase calibrators. The antenna position was first calibrated, then we determined the flux density scale, complex gain, and baseline-based solutions from the calibrator 3C48, and applied them to the target Cas A (3C461). Data for each array were calibrated individually, and then concatenated and imaged. To avoid a negative “bowl” around the source, multiscale CLEAN deconvolution method was used for imaging (Cornwell 2008). We have used Briggs’ weighting with different parameters of robust = −2, −1, 0, 1, 2 to restore images. When robust = 1 and 2, images are in the high random noise of VLA, and rms noise reaches 30 mJy beam−1. In the absolute flux scale uncertainty of 3% (Perley & Butler 2013), there are same integrated flux density and stable noise levels for robust = −2, −1 and 0. Considering surface brightness sensitivity while requiring high resolution, we used robust = 0 for the image restoration and obtained images with an rms noise of 3.0 mJy beam−1.

3. Method

AR95 has performed a detailed study for the temporal evolution of compact radio features in Cas A. The net radial deceleration of compact radio features in Cas A has not been observed. In this section, we have made a new measurement of the proper motion and brightness changes for the radio features based on the higher resolution (1.5″) and sensitivity observations of VLA.

3.1. Image Normalization

The five images have been obtained from difference observation projects over five epochs. These observations exhibit differences in absolute flux calibration and aperture coverage, which leads to the differences of these five images’ reconstruction. In order to minimize the effect of different

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7 https://casa.nrao.edu/
aperture coverage for imaging, image normalization is necessary. In the five images, AR310 (1994.75 epoch) has the highest resolution ($0''56 \times 0''46$) and AD500 (2004.74 epoch) has the lowest resolution ($1''42 \times 1''2$). To compare the flux density of different observations safely, we adopt the Gaussian convolution algorithm to smooth all images into the same beam size of $1''5$.

### 3.2. Selection of Compact Radio Emission Features

Hundreds of compact radio emission features in the remnant of Cas A are evolving rapidly, and parts of the knots are disappearing. To select the radio knots, we denote the location of all local maximum values based on the 1987 image, and construct the contour map. Therefore, we obtain all possible knots in the 1987 image. These knots evolve rapidly, as shown in Figure 1. In this study, we keep the knots having the following features: it can be isolated from the surroundings; clearly visible in the five continuous images of the C band; and its shape has not changed significantly over the span of 17 yr. As a result, 260 radio knots have been kept; parts of them are consistent with the 304 knots compiled in AR95. The position of these knots are shown in Figure 2, and the detailed statistics are given in Table 2.

### 3.3. Measurement of Position and Brightness Relative Change

For the position and brightness change of compact features, the least-squares method is widely used (Tuffs 1986; Anderson & Rudnick 1995). This numerical method allows us to test acceleration or deceleration of individual knots, which can minimize the effect of different apertures coverage at multi-epochs on the variations of large-scale background reconstruction. We have adopted the same algorithm to measure the positions and brightness changes of each radio knot from epoch 1987 to 2004.

First, we use the epoch 1987 image (the earliest image we used, which has a high resolution) as the reference image $A_{ij}$, the other as comparison images $B_{ij}$ (images from epochs 1994, 1997, 2000, and 2004). A small region is set around each knot of the reference image $A_{ij}$. Next, we select a region for each corresponding knots in comparison images $B_{ij}$, which would contain knot for all epochs and is separated from the surrounding emission. Finally, we minimize the quantity in

![Figure 4. The spatial distribution of proper motion of 260 radio knots.]( attached image)
the region by the following method:

\[ T(\xi) = \sum_{i=1}^{I} \sum_{j=1}^{J} Q_{ij}^2(\xi), \]  

(1)

the summation \( T(\xi) \) is performed over all pixels in the region (IJ). Where, \( Q_{ij}(\xi) = A_{ij} - SB_{ij}(\Delta \alpha, \Delta \sigma) - H \), with respect to 4-vector \( \xi = (\Delta \alpha, \Delta \sigma, S, H) \). S is the brightness scaling factor between different epochs, \( \Delta \alpha \) and \( \Delta \sigma \) are the variations of the relative position between image \( A_{ij} \) and \( B_{ij} \), and H is the level of change in the local backgrounds. This summation procedure was performed four times at each radio knots to obtain the relative changes of position and brightness in four comparison images and reference images.

4. Results and Discussion

The position \((x, y)\) and peak brightness of all radio knot samples we studied are given in Table 2. The position respects to the optical expansion center of \( \alpha(1950) = 23^h21^m11^s4, \delta(1950) = +58^\circ32'28''5 \) (Koralesky et al. 1998). The quoted peak brightness is the maximum of the radio emission features. To determine the proper motion, acceleration or deceleration, and brightness change ratio, a nonlinear fitting method has been used. Proper motion \((v_x, v_y)\), acceleration or deceleration
(ax, ay), and brightness change ratio (ΔB/B) fitting results are summarized in Table 2.

4.1. Proper Motions of Compact Radio Knots

We have used a nonlinear fitting method to calculate the positional shifts (Δα and Δσ) as a quadratic function of evolution time (i.e., Δs = v₀t + a t², Δs is the positional shifts of R.A. or decl.), and obtained the proper motion of each radio features. The date of each VLA images adopted in the fitting is the average date of the A, B, C, and D configuration observations of VLA. Most radio emissions in Cas A have decelerated significantly, nonlinear fitting can describe the real evolution of its motion better. From the linear and nonlinear model fits of partial knots’ motion shown in Figure 3, the linear fitting model does not provide a good fit to knots’ motion trajectories, especially for knots with fast motion. The spatial distribution of proper motion vectors of the 260 radio knots is shown in Figure 4. Comparing with the plot of proper motion vectors in AR95, there are no significant systematic differences.

The location of radio expansion center is at α(1950) = 23 h 21 m 07 s ± 0′ 29, δ(1950) = +58° 32′ 25″ ± 2′′ 2 from our measured proper motion results, which is consistent with the center position measured in AR95 within the quoted errors. A linear relationship between proper motion and distance from the radio expansion center has been used to deduce bulk expansion timescales of the remnant in AR95 and Tuffs (1986), which assumes that all radio emission has the same initial velocity and does not show deceleration or experience the same deceleration process.

To track the motion evolution of Cas A, we used the same linear expansion model to estimate the expansion timescales of the remnant in R.A. and decl.. Before fitting the relationship between proper motion and distance from the expansion center, we used the linear fitting method to recalculated the proper motion of radio features to ensure the rationality of this method. Figure 5 shows the fitting results of expansion timescales; the expansion timescale of R.A. is TR.A = 904 ± 10 yr, which is equivalent to the expansion timescale of decl. Tdecl = 910 ± 12 yr. Our measured expansion
timescale conflicts with Tuffs’ (1986) measurement that the expansion timescales of R.A. was longer than decl. significantly. Intriguingly, the expansion timescale in R.A. is approximately equivalent to the expansion timescale in decl., which is consistent with AR95 ($T_{\text{R.A.}} = 866 \pm 8$ yr, $T_{\text{decl.}} = 861 \pm 9$ yr). However, the expansion timescales we obtained are longer. Under the assumption of a same expansion model we detected longer expansion timescales, which indicates that radio emission in the remnant is indeed deceleration.

The knots located at the northeastern and northern edges have relatively high proper motion from Figure 4; the velocity can reach to $\sim 14,500$ km s$^{-1}$ in the north. As shown in Figure 5(a), the knots located at the east and west under the fitting line are not well fitted, which indicates that knots have lower proper motion at the western edge and higher proper motion at the eastern edge. In Figure 5(b), the knots located at the northern are above the fitting line, indicating that the knots with higher proper motion are in the north.

Ejecta interacting with the reverse shock forms a bright radio emission circle with a radius of $\sim 1.7$ pc in Cas A, and a fainter plateau extending to a radius of $\sim 2.5$ pc (Zirakashvili et al. 2014; DeLaney et al. 2014). This radio morphology corresponds to the two knots groups distributed in Figure 6, which can be understood as concentrically expanding shells, as in AR95. Knots experience varying degrees of deceleration at different shells, and the proper motion of knots at the outer shell is faster than at the inner shell obviously. Moreover, the radial expansion ratio of radio emission features outside the bright radio ring increases with the distance from the radio expansion center. The average rate of expansion is about 2100 km s$^{-1}$, while the nonlinearity values of the outer bright radio ring are $\sim 2550$ km s$^{-1}$, and $\sim 1750$ km s$^{-1}$ inner bright radio ring. This expansion timescale in the bright ring region is $\sim 857$ yr, and in the outer region is $\sim 525$ yr. The outer radio emission dynamic age measured close to the overall expansion timescales was measured by Agueros & Green (1999; i.e., $\sim 400$–$500$ yr). Interaction between the remnant and molecular clouds hints at a deceleration of knots in the shell (Kilpatrick et al. 2014, Sato et al. 2008); outer shorter dynamics timescales indicate a smaller deceleration of knots located at the outer shell.

4.2. Accelerations of Compact Radio Knots

Longer expansion timescales have been detected using the same linear expansion model as for AR95, which indicates that the knots in Cas A have already decelerated significantly. In Section 4.1, the proper motion of 260 knots has been measured by using the nonlinear fitting model ($\Delta s = v_0t + a_xt^2$) to fit position shifts ($\Delta \alpha$, $\Delta \sigma$); meanwhile, the magnitude of accelerations $a_x$ has been given. For part knots, the computations of the position shifts appear in the opposite direction for some epochs, and the data of these epochs were excluded in the fitting. For another, in order to calculate the accelerations of each knot, at least four epoch data are kept in

![Figure 8](https://example.com/figure8.png)

**Figure 8.** The histogram of peak flux of compact features we studied.
the fitting (including the reference image). Therefore, part of the proper motions and the accelerations are calculated only based on data from four epochs. Those knots that have position shifts in the opposite direction for more than two epochs have been excluded in determining the used samples.

We have recalculated the accelerations of each knot by sequentially excluding each epoch from the fitting, the average significant level of $a_{\text{R.A.}}$ and $a_{\text{decl.}}$ being around $2\sigma$. For some knots, the obtained accelerations are less than the associated errors, which may be caused by the changes in shape or confusion with other emissions. Checking the spatial distribution of the accelerations, the accelerations field is somewhat disordered but not random noise. To determine whether an individual knots is accelerating or decelerating directly, we project the accelerations onto the direction of its proper motion vectors. The spatial distribution of the acceleration vectors projection is displayed in Figure 7, which shows that $\sim$76% of knots are decelerating. If we take them as a whole, the components of the accelerations in the radial coordinates, R.A. and decl., are $a_{\text{radial}} = -3.9 \pm 2.0 \text{ mas yr}^{-2}$, $a_{\text{R.A.}} = -1.7 \pm 0.7 \text{ mas yr}^{-2}$, and $a_{\text{decl.}} = -2.6 \pm 1.0 \text{ mas yr}^{-2}$, respectively.

Vink et al. (2022) reported the proper motion of the forward and reverse shock of Cas A in X-ray, and demonstrated that the forward shock in the western edge is accelerating. Most of the knots located at the outer edge of the northeast are shown accelerating from the measurement result displayed in Figure 7, but the spatial distribution of acceleration vectors in other regions appears to have no obvious regulations. The histogram peak flux in Figure 8 shows that there is no obvious difference between the acceleration and deceleration distribution, which hints that the acceleration or deceleration of the individual knot has no correlation with the flux density distribution.

We think there are two reasons for the acceleration of radio emissions. One is that the accelerated knots get confused with other radio emissions. Knots that are located in bright emission regions are more easily confused with other radio emissions, and the acceleration is generally less than the quoted error. The second is that the stellar wind density of the remnant’s progenitor is spatially inhomogeneous. Similarity in the morphology and spectra of the adjacent nebulae with the eastern cloud of Cas A indicates the progenitor’s mass loss (Weil et al. 2020). Mass loss leads to the fluctuations in the stellar wind density of the progenitor, which will accelerate while a knot moves from the high-density region to the low-density region.

4.3. Brightness Changes of Compact Radio Knots

In the brightness change measurement, to avoid the influence of the difference of synthetic aperture coverage in difference
epochs on the flux density and the shape of large-scale structures, we have smoothed all continuum images into the same beam size (i.e., 1″5 × 1″5). Brightness changes have been measured using the least-squares method in Section 3.3, and the brightness change fraction was derived by nonlinear fitting. The spatial distribution of fractional changes in brightness is displayed in Figure 9. The flux of Cas A is constantly fading (Reichart & Stephens 2000; Trotter et al. 2017). However, our measurement shows that ∼62% of the radio knots are brightening with an average rate of ∼2.2%, these knots occupy only a small fraction of the total emission of Cas A.

AR95 has reported that the large-scale emission and compact features in Cas A are brightening with an average rate of ∼1.6% yr\(^{-1}\). In the current work, ∼62% of the compact features are brightening, and the brightness change fraction varies in different regions. The compact features on the bright radio ring (90′−130′) have a relatively low brightening rate of ∼1.4% yr\(^{-1}\). The average brightening rate of compact features in the inner region of the bright radio ring (<90′) is ∼2.1% yr\(^{-1}\); this value is mainly the contribution of the southwest region inside the bright radio ring, which is brightening rapidly. In the diffuse plateau region, compact features are brightening at a relatively fast rate of 3.7% yr\(^{-1}\).

Bright radio emissions rely on the synchrotron radiation emitted by electrons moving in the magnetic field; a high radio emission means a high magnetic field for a given number density of electrons. Most of the radio-bright knots are distributed in the bright ring of Cas A from Figure 2, whereas the primary site of cosmic-ray acceleration is located in the forward-shock front (Vink & Laming 2003; Holder et al. 2012). Moreover, studies of radio spectral index have shown no evidence of reacceleration in bright radio knots (Anderson & Rudnick 1996; Wright et al. 1999). These studies indicate that brightness variations are links to the fluctuations of the magnetic field directly. Therefore, the fading, brightening, disappearing, or new appearing of compact features in Cas A is likely to be the result of magnetic field variations.

5. Summary

We have obtained five images of Cas A at 5 GHz in all four configurations of the VLA from 1987 to 2004, while all images have been smoothed to the same resolution of 1″5. We measured the proper motion and brightness changes of compact radio features in Cas A, gave the radio expansion center locates at \(\alpha(1950) = 23^h 21^m 99.7^s ± 0.29^s\), \(\delta(1950) = +58^\circ 32′ 25.2″ ± 2″2\), and the expansion timescales of R.A. and decl.: \(T_{\text{R.A.}} = 904 \pm 10\) yr and \(T_{\text{decl.}} = 910 \pm 12\) yr, respectively. Because of the limit of the angular resolution of observation, the uncertainty of the proper motion measurement will lead to different estimations for the expansion timescale. Benefiting from the improvement in angular resolution, the expansion timescale is more reliable.

The remnant is overall in a decelerating phase, but only about three-quarters of compact radio knots are decelerating. Some radio knots with acceleration are in the region of radio emission confusion and these radio knots may not really be in acceleration. In addition to the effect of measurement errors in the radio emission confusion regions, the compact features’ acceleration phenomenon suggests that there is density fluctuation in the stellar wind of Cas A’s progenitor. Over 17 yr, the brightness of the compact radio features in Cas A has changed significantly, which suggests that the magnetic field is changing rapidly.

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