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Polarization structure and variability of the BL Lac object S4 0954+658

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We present the results of a multi-frequency analysis of the enigmatic BL Lac object S4 0954+658. We have analyzed three epochs of dense VLBA observations with full polarization at 22 GHz and 8 GHz and one epoch at four frequencies 5 GHz, 8 GHz, 15 GHz, and 22 GHz taken in 1996-1998. We found that the jet is of a prominent helical shape and that the jet ridge line changes dramatically with time. The jet ridge line becomes wider with time and the position of the jet ridge line bend shifts along the jet with a speed of 1.5±0.1 c. The Kelvin-Helmholtz instability can explain such changes of the jet ridge line. We estimate the sound speed of the S4 0954+658 jet $a_{jt} = 0.5 \pm 0.1c$ and the Mach number $M_{jt} = 10 \pm 0.7$.

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1. Introduction

The BL Lac object S4 0954+658 (z=0.368, [5]) is a well known intra-day variable source, which shows flux-density variations on a timescale of several hours (e.g., [11]). Fast variability in this source was observed in the total flux-density light curves, as well as at high precision Very Long-Baseline Interferometry (VLBI) images [2]. The source S4 0954+658 was detected in gamma-rays by the EGRET observatory [7]. The VLBI structure of S4 0954+658 was studied by e.g. [1]. Model-fitting of the S4 0954+658 jet performed by [10] showed great uncertainty in speed estimations. The speeds are either around zero (jet components are stationary), or $\beta_{app} > 50$. In this proceeding we discuss the jet structure and evolution from the dense VLBI observations with full polarization.

2. Observations

The source was observed during four epochs of observations in 1996-1998 at two frequencies 8 GHz and 22 GHz with full polarization. One epoch (epoch C, 1997.2) was observed at four frequencies 4.8 GHz, 8 GHz, 15 GHz, and 22 GHz in order to study the detailed rotation measures distribution and the multi-frequency properties of the source. We have also used in the analysis the multi-frequency VLBI data from [8] taken on 2006 July 2 and from [6] (epoch 2004.3) for the detailed investigation of the source time variability.

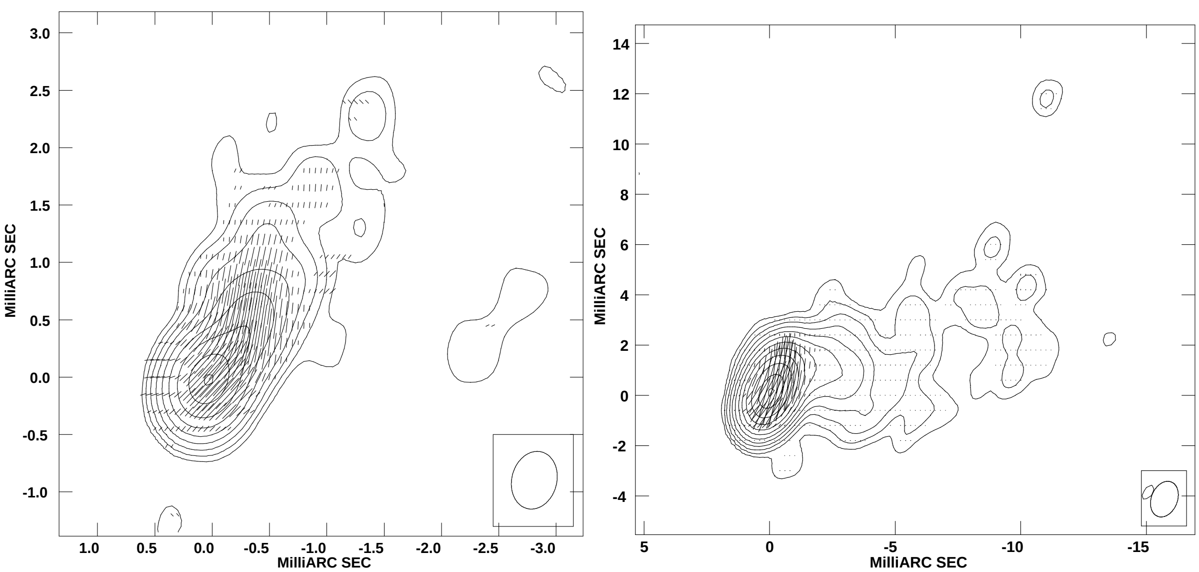

Figure 1: VLBI map of S4 0954+658 at 22 GHz (left) and 8 GHz (right). The intensity I is plotted with the polarization sticks superimposed.

3. Results

The jet of S4 0954+658 is going in the north-west direction and experiencing multiple bends at ∼2 mas, ∼4 mas, and ∼10 mas, following a prominent helical path. Figure 1 shows maps

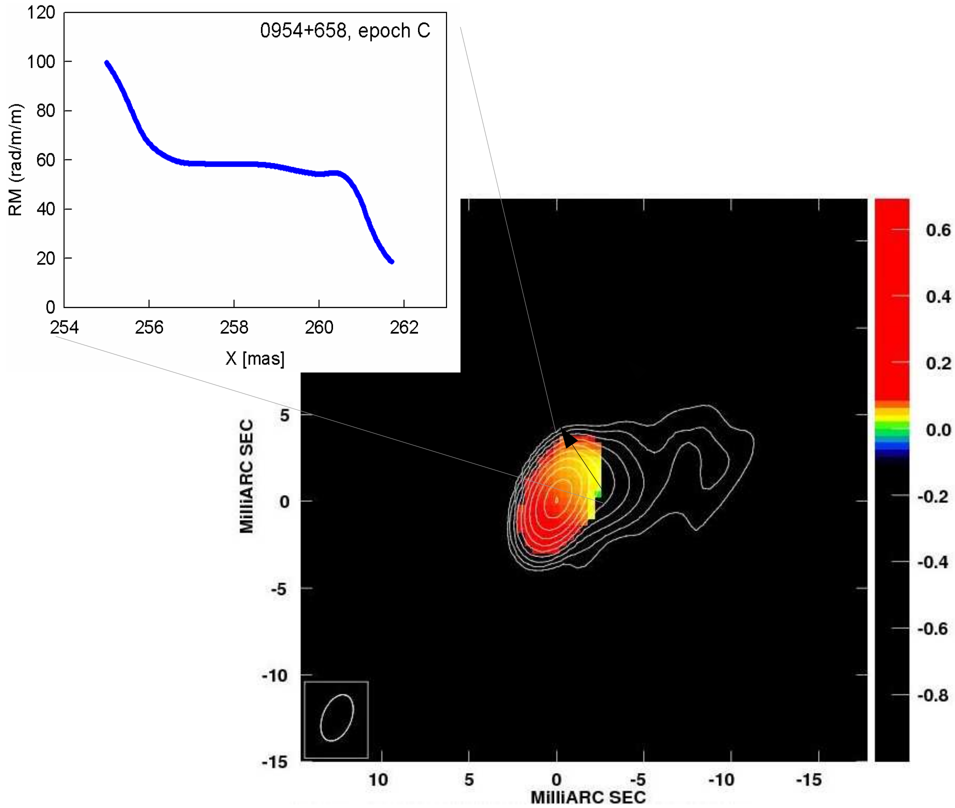

Figure 2: The rotation measure distribution in the core of S4 0954+658.

of S4 0954+658 at 22 GHz (left) and 8 GHz (right) at epoch C (1997.2). The restoring beam is shown as an ellipse in a corner of the image. The polarization vectors are mostly aligned with the jet direction at all frequencies except for the core region. The rotation measures distribution in the core at epoch C, constructed for four frequencies 5 GHz, 8 GHz, 15 GHz, and 22 GHz are shown in Fig. 2. The rotation measures are changing across the jet from 20 rad/m/m to 100 rad/m/m, suggesting a rotation measure gradient across the jet, which confirms the gradient in the S4 0954+658 core found by [8]. This is an evidence for the presence of a helical magnetic field geometry in the Faraday rotating medium.

We performed model-fitting of the source *I* and *P* visibilities with the circular Gaussian components using the model-fitting software in the Difmap and the Brandeis VLBI packages [9]. The jet consists of 5 individual components moving outward with almost similar speed of 4.9±0.4 c (0.36 mas/yr). Figure 3 shows the core separation between the Gaussian components and the core component versus time at 22 GHz. Figure 4 (left) shows the jet ridge lines time evolution at 8 GHz. The points on the plot correspond to a position of jet components obtained from the model-fitting. We found that the jet experiences dramatic changes with time. The jet is extremely curved at the first epoch, then gradually flattens and is almost a straight line at epoch D. Therefore, in order to study the jet ridge line evolution, wrote a piece of software and calculated the jet ridge lines for all

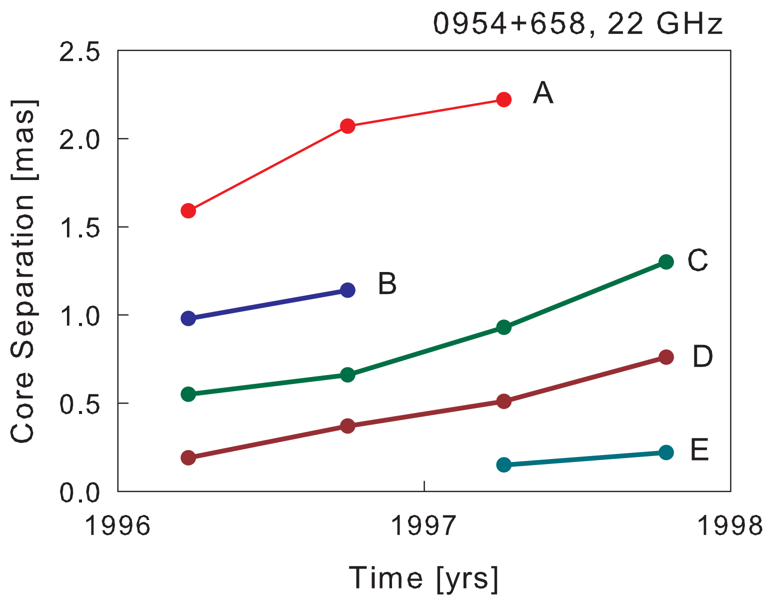

Figure 3: Core separation versus time at 22 GHz.

epochs and all frequencies fitting a Gaussian function across the mean jet direction. We estimated the position of the jet ridge line as an averaged over 3 pixels position of the maximum of the fitted Gaussian function. Figure 4 (right) shows the jet ridge lines for each epochs at 8 GHz for the epochs A - D and for the epochs 2004.3 and 2006.6 from [8] and [6]. The jet ridge line changes dramatically with time. It becomes wider (the width of the helical wave changes from about 1 mas to 1.7 mas) and the maximum is gradually shifting along the jet, from about 1.7 mas to 2.8 mas over eight years of observations. Fitting a Gaussian function into the first four milliarcseconds of the jet ridge line, we can investigate how the position of the maximum of the helical wave is moving. Figure 5 shows the time evolution of the X (left) and Y (right) coordinates of the maximum. The position of the maximum is changing almost linearly with time and we can estimate the speed of the shift by fitting a linear regression. The speed of the X coordinate of the maximum is 0.11±0.02 mas/yr, which corresponds to 1.5±0.1 c. The speed of the Y coordinate of the maximum is 0.09±0.01 mas/yr and is very similar to the X coordinate.

4. Discussion

For the first time we directly detected from the VLBI observations the evolution of the jet ridge line and shift of the helical wave with time and measured the speed of the instability wave propagation along the jet to be $1.5 \pm 0.1c$. The most likable explanation of the helical form of the jet ridge line and the shift of the ridge line is the Kelvin-Helmholtz instability in the jet plasma. The Kelvin-Helmholtz instability appears when two layers of fluids with different speeds are present and it can cause a helical shape of the jet. It also predicts that the helical wave becomes wider with time and that the wavelength of the helical wave increases [3], [4]. Therefore, using the formulas for the physics of the Kelvin-Helmholtz instability we can estimate physical parameters of the jet.

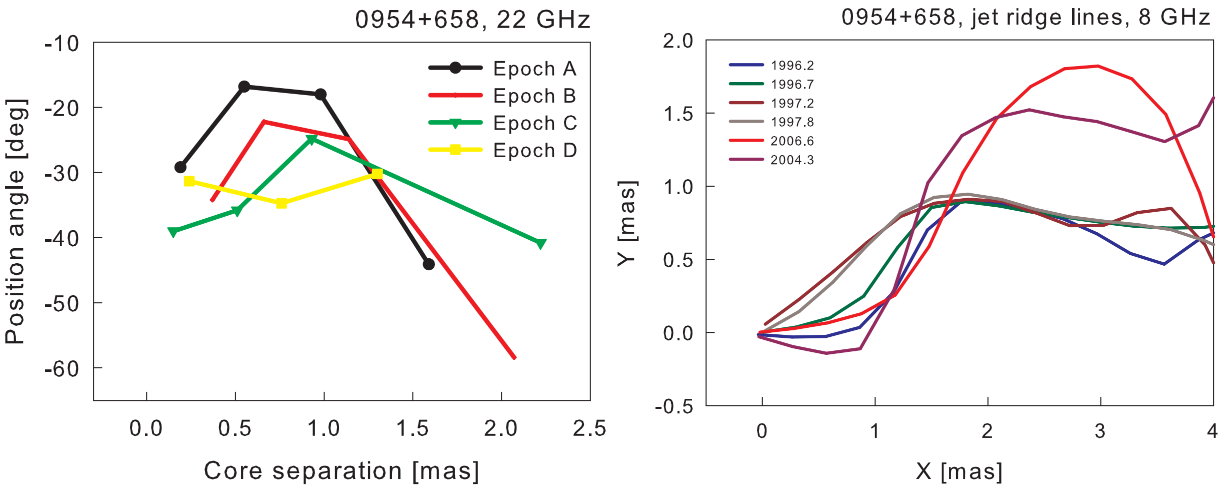

Figure 4: The jet ridge lines of S4 0954+658 at 8 GHz for various epochs. Each color represents different epoch of observations. The jet ridge line is getting bigger with time and the position of the maximum is moving along the jet.

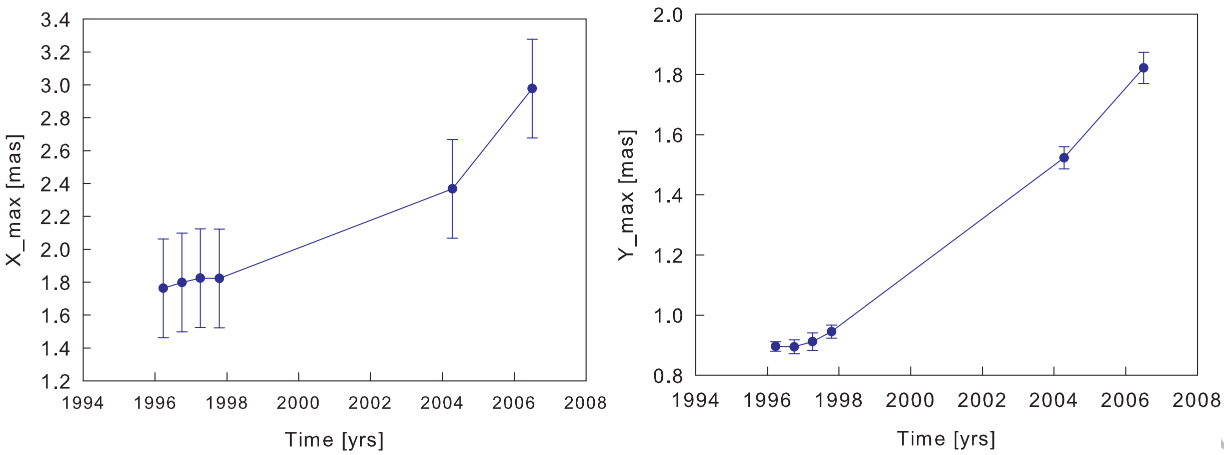

Figure 5: Evolution of the X (left) and Y (right) position of the maximum of the jet ridge lines with time.

Following analytical approach of [3], [4], we can estimate the sound speed of the jet a_{jt} from the equation:

$$v_w \approx \frac{v_{jt} - a_{jt}}{1 - a_{jt} v_{jt}/c^2}, \tag{4.1}$$

where v_w is the wave speed, and v_{jt} is the jet speed. We know the jet speed from the jet model-fitting and kinematics is $v_{jt} = 4.9 \pm 0.4c$. The wave speed we have estimated in the previous section from movement of the position of the maximum $v_w = 1.5 \pm 0.1c$. Therefore, using the former equation, the sound speed of the jet is $a_{jt} = 0.5 \pm 0.1c$. We can also estimate the Mach number of the jet $M_{jt} \equiv v_{jt}/a_{jt}$ to be $M_{jt} = 10 \pm 0.7$, because we know both sound speed of the jet and the jet speed.

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