THE FIRST KINEMATIC DETERMINATION OF MILLION-YEAR PRECESSION PERIOD OF ACTIVE GALACTIC NUCLEI

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ABSTRACT

Short precession periods like the 164 day period of SS433 can be well determined by observations of timescales longer or much longer than the precession period. However, this does not work for sources with precession periods of millions of years. This Letter utilizes the particular morphologies of X-shaped sources, so that the three-dimensional kinematics of lobes can be obtained. Thus, for the first time, the million-year precession period of X-shaped sources by an observer on the Earth can be determined elegantly: 6.1 ± 1.5 Myr, 1.8 ± 0.5 Myr, and 3.2 ± 1.2 Myr for 3C52, 3C223.1, and 4C12.03, respectively. The result naturally explains the asymmetry displayed in the morphology of these sources, and the effect of propagation time on the diversity of morphologies is well demonstrated. The precession period may originate from long-term effects of a binary supermassive black hole system, which is a potential source of gravitational wave radiation.

Key words: galaxies: active – galaxies: jets

Online-only material: color figures

1. INTRODUCTION

First discovered in 1974 (Hogbom & Carlsson 1974) and with a rapidly growing sample in recent years (Cheung 2007), the peculiar radio morphologies, X-shaped extragalactic radio sources, are characterized by two low surface brightness wings oriented at an angle to the high surface brightness lobes, which gives them their X shape. Recently, X-shaped galaxies are being considered as a potential transition between Fanaroff–Riley (FR) type I and II (Landt et al. 2010).

Several formation scenarios have been proposed. One is the backflow of plasma from the active lobes into the wings (Leahy & Williams 1984; Capetti et al. 2002; Hodges-Kluck & Reynolds 2011) with subsequent buoyant expansion. It has been argued that the expansion of wings is subsonic, and it becomes untenable for X-shaped sources with wings longer than the active lobes (Dennett-Thorpe et al. 2002). The second scenario is the conical precession of the jet axis (Parma et al. 1985; Mack et al. 1994), which implies a scenario of ballistic jet motion plus jet precession, and predicts a spiral pattern. However, this model requires a specific coincidence of the positions at which the source first switched on and its position now. Moreover, it cannot explain the notable asymmetry in 3C223.1 (Dennett-Thorpe et al. 2002).

Two other explanations have received much attention lately. They are in agreement that the wings are relics of the previous jet, and the lobes are produced by the jet in action. Thus, regardless of the mechanism of the change of the jet axis, we establish a coordinate system in which the two-dimensional morphology can be fitted by the simplest geometry. And together with the constraint imposed by the simultaneous arrival time of photons from the south and north lobes of an X-source, the most collimated components of the source first switched on and its position now. Moreover, it cannot explain the notable asymmetry in 3C223.1 (Dennett-Thorpe et al. 2002).

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2. THE NEW APPROACH

The non-ballistic model (Gong 2008) has been used to interpret the non-radial jet motions of active galactic nuclei (AGNs; Kellermann et al. 2004; Agudo et al. 2007; Lister et al. 2009) in which a knot can be produced by a continuous jet interacting with ambient matter in different directions during the precession of the jet axis. Approximately equal knot–core separation is expected when the power of the jet and matter density of the surrounding medium are unchanged in different directions. Such a constant core–knot separation avoids the specific coincidence of the positions required by the conical
precession model. And due to the X-shaped morphologies, which display similar non-radial characteristic as other AGN sources, it is conceivable that the non-ballistic model can be applied to the X-sources.

This model can be described by two simple geometric equations. Projecting a knot, \( i \), with knot–core separation, \( R_i \), to the coordinate system \( x-y-z \), we have

\[
\begin{align*}
R_{xi}^i &= R^i [\sin \lambda \sin I \cos \eta^i i + \cos \lambda \cos I], \\
R_{yi}^i &= R^i [\sin \lambda \sin \eta^i i], \\
R_{zi}^i &= R^i [\cos \lambda \sin I - \sin \lambda \cos I \cos \eta^i i],
\end{align*}
\]

(1)

where \( \lambda, I, \eta_i, \) and \( R \) represent the opening angle of the precession cone, the inclination angle between the jet rotation axis and the line of sight (LOS), the precession phase, and the knot–core distance, respectively, as shown in Figure 2.

In Equation (1), the \( x \)-axis is toward the observer. Rotating around the \( x \)-axis for angle \( \xi \), so that the new \( y \)-axis (\( \Delta \Omega \)) will point north and the new \( z \)-axis (\( \Delta \alpha \)) will point east. Therefore, the coordinate of a feature in the plane of sky is given by

\[
\begin{align*}
R_{xi}^i &= R^i [\sin \lambda \sin \eta^i i \sin \xi] \\
+ R^i [\cos \lambda \sin I - \sin \lambda \cos I \cos \eta^i i] \cos \xi,
\end{align*}
\]

where \( \xi \) is the precession phase of a knot, \( \eta^i = \Omega t + \eta_0^i \), is the initial phase

\[
R_{zi}^i = R^i [\sin \lambda \sin \eta^i i] \cos \xi \\
- R^i [\cos \lambda \sin I - \sin \lambda \cos I \cos \eta^i i] \sin \xi.
\]

(2)

Equation (1) predicts an ellipse, the shape of which is determined by four parameters, \( \xi, \lambda, I, \) and \( R \). Searching in their parameter space as shown in the parentheses in Table 1, the best combination of parameters corresponding to the solid ellipses in Figure 1 can be found.

Once the best-fit ellipse for a morphology is found, the precession phase of a knot, \( \eta^i = \Omega t + \eta_0^i \), can be given, where \( \Omega \) is the precession velocity of a jet and \( \eta_0^i \) is the initial phase of a knot. However, the precession time, \( t \), and the precession velocity, \( \Omega \), cannot be separated from \( \eta^i \). In other words, \( \Omega \) cannot be obtained by such a two-dimensional morphology fitting alone.

Fortunately, a simple constraint can be found to split \( \Omega \) and \( t \), therefore allowing us to determine the precession period by three-dimensional kinematics. The time of emission of a photon from a knot, \( t'_{\text{emit}} \), can be measured in the reference frame at rest to the core of an X-shaped source. This photon can reach an observer on Earth at \( t_{\text{arr}} = t'_{\text{emit}} + d/c - x'/c \), where \( d \) is the core–observer distance and \( x' \), which is equivalent to \( R_{zi}^i \) of

Figure 1. Observed morphology of three X-shaped sources (Lal & Rao 2007) and the fitted traces (ellipses) given by the non-ballistic model. The north is up and the east is to the left. The solid ellipses correspond to the best-fit parameters of Table 1, and the dashed ellipses correspond to 20% increase in parameters, \( I, \lambda, \) and \( \xi \) (while holding others constant) for 3C52, 3C223.1, and 4C12.03, respectively. The red dots represent components of a morphology which the ellipses try to fit. A red circle is the “radius” of the lobe through which the error in precession phase is estimated.

(A color version of this figure is available in the online journal.)

Figure 2. Schematic illustration showing an X-shaped source under the non-ballistic precession scenario. Different precession states of the X-sources are equivalent to the observation of one source at different view angles as LOS\(_1\) and LOS\(_2\), and hence different morphologies.

(A color version of this figure is available in the online journal.)
Equation (1), is the projection of the knot–core separation onto LOS. For simplicity, we can define a time, $t_0 = t_{\text{emit}} - d/c$, such that the time taken for a photon from a knot to the observer can be represented simply by $t_0 = t'_{\text{emit}} - x'c$.  

Also measured in the reference frame at rest to the core of an X-shaped source, the precession time of a knot can be synchronized to the emission time, $t' = t'_{\text{emit}}$, where $t'$ is given by $n' = n + n_0'$. Thus, the condition of observing the two signals from opposite lobes ($i = 1, 2$ denote the north and south lobes, respectively) at the same time becomes

$$t' - x'/c = t_0.$$  

Certain precession phases result in $t' - x'/c > t_0$, which means that the signal has not arrived to the observer yet and is hence unobservable, whereas $t' - x'/c < t_0$ means that the received signal is from a knot that has been at its emitting site for a period of time. If it has afterglow emission that is above the threshold of detection, then it is still observable.

Therefore, a knot which is unobservable in the case of zero cooling time, $t' - x'/c < t_0$, becomes detectable provided the emissivity of the knot is above the threshold of detection in the cooling time, $t_0$. Such an emission reaches the Earth at

$$t_0 + t' - x'/c = t_0.$$  

Consequently, with increasing separation of the active lobes, a knot in the wings corresponds to a larger $t_0$, such that it appears more diffused and faint until it becomes unobservable.

Limited by the expansion speeds of low-luminosity FR-II sources, the advance speeds of X-sources are likely not greater than 0.04c (Dennett-Thorpe et al. 2002). Such non-relativistic speeds correspond to a negligible Doppler boosting effect, such that the flux of a knot depends primarily on the emissivity. Hence, the precession periods at the frame of the source, $P_p$, and at the Earth, $P_p^{\text{obs}}$, are related by $P_p(1+z) = P_p^{\text{obs}}$, where $z$ is the redshift of the source.

Multiplying the precession velocity, $\Omega$, at the two sides of Equation (3), we have

$$n' - n_0' = \Omega x'/c = n_0,$$

where $n_0 = \Omega t_0$. Apparently, an X-source is observed when the photons from the lobes arrive at the Earth simultaneously. At this moment the initial phases of the two lobes can be treated as $n_0' = n_0'$, without losing generality. Thus, $n_0'$ of Equation (5) can be canceled.

The $n'$ and $x'$ of the north and south components can be obtained by fitting the two-dimensional X-shaped morphology. The process consists of simply putting the geometrical parameters of Table 1 (except $\Omega$ and $\Omega^{\text{obs}}$) into Equation (2) and then finding the best-fit parameters through minimizing the sum of the square of the residuals of the predicted ellipse from the observed morphologies. The pair ellipses (with the same group of geometric parameters) for each source are required to fit 7–8 components represented by the red dots in Figure 1. The solid ellipses of Figure 1 represent the best-fit ones corresponding to parameters shown in Table 1, and the dashed ellipses correspond to 20% increase in parameters $I$, $\lambda$, and $\xi$ (while holding others constant) for 3C52, 3C223.1, and 4C12.03: respectively. Hence, the role of these parameters in the formation of an ellipse is exhibited, i.e., for 4C12.03: the 20% increase in $\xi$ from its best value changes not only the shape of the dashed ellipse, but also its position, in which case, the morphology cannot be fitted, no matter what the other parameters are.

Although making an ellipse through 7–8 points in the morphology strongly constrains the fitting parameters, we did find that the morphology of 3C223.1 can be fitted by another combination of parameters, i.e., with $R$ approximately twice and $I$ half of the corresponding parameters of Table 1. However, such a solution predicts a much larger discrepancy in propagation time between the northwest (NW) and southeast (SE) structures than that of Table 1, which is contradictory to the nearly symmetric structure of 3C223.1, as analyzed in Section 3. It is thus excluded.

Differentiating Equation (2), one has $\Delta R^2 = \sum f_j \Delta \sigma_j$, where $\sigma_j$ (j from 1 to 4) denote $\lambda$, $I$, $\eta$, and $R$, respectively, and $f_j$ correspond to their partial differentiations, respectively. If $\Delta R^2$, where $\kappa$ represents $\alpha$ and $\delta$ of Equation (2), could be as large as the size of a lobe as shown by red circles in Figure 1 (which is attributed to the error of the precession phase of a lobe), then the errors of $\sigma_j$ can be obtained by solving four equations, $(\Delta R^2)^2 = \sum f^2_j (\Delta \sigma_j)^2$, corresponding to two lobes, $i = 1, 2$ (the north and south), of a source. This gives conservative errors (up to 43%) to the best-fit parameters of Table 1, which considerably exceed the 20% parameter errors corresponding to the deviation between the solid and dashed ellipses shown in Figure 1.

Although the two-dimensional morphology fitting perpendicular to the LOS can give $n'$ and $x'$, the most interesting parameter, $\Omega$, cannot be extracted from Equation (5). Since the NW and SE structures indicate that photons from them must arrive at the Earth simultaneously, this can be treated as another constraint (one dimension) along the LOS. The two active lobes (the north and south lobes) with the shortest cooling time always satisfy $t' - x'/c = t'_0 - x'_0/c = n_0 - \Omega^2 x'/c$, no matter if $t_0 \approx t'_0 (x'_0 = x_0)$, or if these values differ largely. Hence the kinematics of the two active lobes of an X-source reads, $\eta' - \Omega^2 x'/c = \eta - \Omega^2 x/c$, which includes three-dimensional constraints, and from which $\Omega$ can be extracted.
the core of this X-source. This corresponds to the observation of the precession velocity, estimated by the size of the lobes. The jet precession velocity of a source, $\Omega$, is thus constrained in the small regions, ABCD.

(A color version of this figure is available in the online journal.)

To obtain $\Omega$ and its error from Equation (5), both $\Omega$ and $\eta_a$ can be ordered as variables. Thus, Equation (5) corresponds to two lines ($i=1,2$), the cross point of which, $(\Omega, \eta_a)$, represents that the two signals arrive on the Earth simultaneously, as shown in Figure 3. With $\eta'$ and $x'$ of the north and south lobes obtained through morphology fitting (two dimensions) and utilize the constraint on photon arrival time (one dimension), the cross point $(\Omega, \eta_a)$ can be determined by Equation (5), through which the precession velocity, $\Omega$, can be constrained into a small range elegantly, as shown in Table 1. The error of $\Omega$ is determined by the errors of $\eta'$ and $x'$, where $\Delta x'$ can be given by the error propagation of parameters in Table 1 via Equation (1), and $\Delta \eta'$ is assumed to correspond to the “radius” of a lobe.

3. ASYMMETRY

The fitting parameters of Table 1 indicate that the phase discrepancy of the two lobes is $\delta \eta_{12} = 185^\circ$ and $\delta \eta_{21} = 189^\circ$ for 3C52 and 3C223.1, respectively. The $\approx 180^\circ$ phase discrepancy corresponds to the observation of an X-source through the LOS$_2$ of Figure 2. Correspondingly, $t^1 - x^1/c = t^2 - x^2/c$ is satisfied in case $x^1 \approx x^2$ and $t^1 \approx t^2$. As the times $t^1$ and $t^2$ increase, the values of $x^1$ and $x^2$ change similarly. Therefore, the emission from the lobes and wings can arrive the Earth at approximately the same time. Consequently, the SE and NW structures of these two sources appear comparable in length and size.

In contrast to these two X-sources, the north and south lobes of 4C12.03 correspond to a phase discrepancy of $\delta \eta_{12} = \eta^2 - \eta^1 \approx -270^\circ$ instead of $\approx 180^\circ$, by the fitting parameters of Table 1. This means that the photons from the active south lobe, which should differ by approximately $\approx 180^\circ$ to the precession phase of the north lobe, have not yet reached the observer on the Earth ($t^2 - x^2/c < t_0$), although such a lobe is observable at the core of this X-source. This corresponds to the observation of such a source through the LOS$_1$ of Figure 2. Therefore, $t^1 - x^1/c = t^2 - x^2/c$ is satisfied in case $x^1$ and $x^2$ ($t^1$ and $t^2$ also) differ significantly. Such a discrepancy in $x^1$ and $x^2$ results in a southwest (SW) pattern compared with that of northeast (NE). Hence, the significant asymmetry of 4C12.03 is well understood.

The north and south lobes of 4C12.03 obviously differ in size. By the fitting parameters of Table 1, the active north lobe possesses the maximum $t^1$ and minimum $\eta^1$ (due to $\Omega < 0$ in 4C12.03), which means that knots of $t > t^1$ and $\eta < \eta^1$ do not exist in the NE pattern at all. This is in agreement with both observers on the Earth and at the core of this X-source. Consequently, the emission of this lobe region can only be extended by the past (cooled) components, with $t < t^1$ and $\eta > \eta^1$.

Contrarily, for the SW pattern, its emission can be extended by both the past components with $t^2 - x^2/c < t_0$ and by some “future” components with $t^2 - x^2/c > t_0$ because components with $t > t^2$ and $\eta < \eta^2$ do exist near the “south lobe” (which would be observable at the core of this X-source) and the cooling emission of such “future” knots can contribute to the brightness of the “south lobe” as well by $t^2 + t^2 - x^2/c = t_0$ (where $x_f$ denotes the “future” emission site). Therefore, the one-way extension of the NE lobe and the two-way extension of the “SW lobe” lead to a larger “south lobe” than that of the NE one.

To analyze the fine asymmetry in these X-sources, Figure 4 is introduced, which is obtained as follows. Putting the obtained $\eta'$ and $x'$ through the fitting of morphologies of three sources of Figure 1 into Equation (5), then ordering $\Omega = \text{const}$, the phase corresponding to the time of arrival, $\eta_a$, versus the phase of precession, $\eta$, can be obtained as shown in Figure 4, which is actually the evolution of $t_0$ and $t$ of the two active lobes.

As shown in Figure 4, each source has its own $\eta - \eta_a$ curve and horizontal dashed line, $\eta_a$, which cross with a misalignment angle. In both 3C52 and 3C223.1, the misalignment angles of the south lobe are smaller than those of the north lobe. Moreover, the discrepancy in the misalignment angles of the north and
south lobes is more obvious in 3C223.1 than in 3C 52. This explains the deviation in surface brightness of the NW and SE lobe regions in 3C223.1, as shown in Figure 1, because the region near the south lobe is closer to the horizontal line, \( \eta_a \), than that of the north one, which corresponds to a shorter cooling time. Hence the linking of the south lobe and its neighboring wing region has higher surface brightness than those of the north one.

4. DISCUSSION

By the fitting of Figure 1 and parameters of Table 1, precessing across the lobe-wing region takes 1.5 Myr, 0.8 Myr, and 1.4 Myr for 3C52, 3C223.1, and 4C12.03 (NE pattern), respectively, the timescale of which corresponds to the cooling time discrepancy between the active lobe and the tail of wing of these sources. Interestingly, the timescale is consistent with the firm upper limits on the particle ages of 34 Myr for 3C223.1, and the estimation of the timescale of reorientation of the jet axis of no more than a few Myr based on spectral gradient (Dennett-Thorpe et al. 2002).

Beside the temporary processes such as merger of SMBBH or disk instability (Merritt & Ekers 2002; Dennett-Thorpe et al. 2002), the change of jet orientation displayed in X-shaped morphology can also be originated from a binary effect (Begelman et al. 1980), which can be either relativistic geodetic precession or Newtonian-driven jet precession (Katz 1997). An SMBBH system with an orbital period of 20 years, and with a typical X-source black hole mass of \( 5 \times 10^8 M_\odot \) (Mezcua et al. 2011) and companion mass of \( 1 \times 10^7 M_\odot \), predicts a precession period of 0.6 Myr by the geodetic effect and a precession period of 1.0 Myr (with disk radius of 10 Schwarzschild radius) by the Newtonian-driven effect. Consequently, the \(~\text{Myr}\) timescale displayed in the three X-sources can be well interpreted by either of the two binary effects. This provides additional evidence to the link between X-sources and SMBBHs. Moreover, the correlation of black hole mass with X-ray luminosity and radio luminosity (Merloni et al. 2003; Falcke et al. 2004), as well as the characteristic timescale of the X-ray variability found in AGNs and X-ray binaries (McHardy et al. 2006; Körding et al. 2007; Mirabel 2006), suggest that black hole physics likely scales with mass. The \(~\text{Myr}\) precession periods of the three X-sources revealed here further support such a correlation with black hole mass.

In the non-ballistic precession model, the diversity of the morphology of X-sources can be simply understood by the received photons from emission sites at different precession cones. The technique is applicable to other X-sources, especially the X-shaped candidates (Cheung 2007) in the future.

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