Twin-jets as a potential distance detector

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ABSTRACT

A preview study of using observational data of proper motions and Doppler shifted velocities of twin-jets to determine the distance of sources inside and outside our galaxy is made. We investigate the feasibility of this method by studying the uncertainty of the distance caused by the uncertainties of the measured quantities. It shows that, when the motion of components of the jet is relativistic, then the uncertainty of the distance is within the same order of the uncertainties of the measured values of proper motions and Doppler shifted velocities. In particular, when assuming the pattern speed equals the flow speed in the jet, for 10\% uncertainties of the measured quantities, the uncertainty of the distance caused by them would be well within 13\%. With current technique, this method is realizable. For the convenience of choosing sources to observe, some sources as potential targets are also listed in this paper.

\textbf{Key words:} distance scale — galaxies: active — galaxies: jets — galaxies: nuclei

1 Introduction

Distance measurement is a long-lived task in astronomical science. The distance of faraway objects can be determined if its real size or luminosity is known. This strongly relies on the discovery of some standard candles or rods. For example, the peak brightness of type Ia supernovae has been served as a distance indicator and was used to determine the Hubble constant (see, e.g., Brach 1992). So far, the most reliable measurement of the distance for extragalactic sources might come from the observation of NGC 4258. Being observed with VLBI, direct measurement of orbital
motions in a disk of gas surrounding the nucleus of this galaxy was made by tracking individual maser features from 1994 to 1997, where proper motions of masers as well as Doppler shifted velocities were obtained (Herrnstein et al. 1999).

VLBI observations have revealed the typical core-jet structure for many AGNs. According to the unified schemes, an AGN possesses in its compact core a supermassive black hole surrounded by an accretion disk, and it is always assumed that there is a twin-jet beamed from the center of the core along the axis of the disk (see, e.g., Urry and Padovani 1995). For a relativistic beaming, there will be a Doppler boosting for the flux of components of the jet, with \( f(\nu) = \delta^p f_0(\nu) \), where \( f_0(\nu) \) is the flux density which would be observed in a reference frame moving with the jet material, \( f(\nu) \) is the flux density observed by us, \( \delta = \sqrt{1 - \beta^2/(1 - \beta \cos \theta)} \), and \( p \) can take on the values \( 2 + \alpha \) (for a continuous jet) and \( 3 + \alpha \) (for a discrete component) for \( f(\nu) \propto \nu^{-\alpha} \) (see, e.g., Pearson and Zensus 1987). Due to the Doppler boosting effect, the flux of an approaching component will be obviously amplified, while that of a receding component will be significantly reduced. Therefore, one expects to observe many approaching components rather than receding ones, and this is true. In fact, we find the core-jet rather than twin-jet structure for the great majority of AGNs observed to date. However, several twin-jet sources were detected recently, both inside and outside our galaxy (those inside the Galaxy are always called microquasars). Some were measured with proper motions of ejected components (see, e.g., Mirabel and Rodriguez 1994, Taylor and Vermeulen 1997), while others were detected with Doppler shifted velocities (see, e.g., Crampton et al. 1987).

It is interesting that proper motions of twin-jets can be used to estimate the Hubble constant. This idea can be traced back to as early as 1980s (see, Marscher and Broderick 1982). It is not until the recent discovery of proper motions that the idea of using this method can be realized. The most successful one was achieved by Taylor and Vermeulen (1997). The data of proper motions can also be used to estimate the pattern speed and the angle to the line of sight of the jet if the distance of the source is known. However, the flow speed in the jet and the angle to the line of sight of the jet can be well determined by Doppler shifted velocities alone, without depending on any knowledge of the distance of the source. As a consequence, one can combine this result together with proper motions to determine the distance without referring to any “standard” quantities (see, Mirabel and Rodriguez 1994). In this paper, we make a preview study of combining the observations of proper motions and Doppler shifted velocities of twin-jets to determine the distance of sources,
trying to find out if this method is realizable with current technique.

2 The method

According to the theory of relativity, the apparent transverse velocity of a component is related to the angle to the line of sight and its speed (Rees 1966, 1967). For a twin-jet, the apparent transverse velocities of the approaching and receding components follow

\[
(v_{\text{app}})_A \equiv \mu_A D = \frac{\beta_p \sin \theta}{1 - \beta_p \cos \theta} c \quad (\theta \leq \frac{\pi}{2}),
\]

(1)

\[
(v_{\text{app}})_R \equiv \mu_R D = \frac{\beta_p \sin \theta}{1 + \beta_p \cos \theta} c \quad (\theta \leq \frac{\pi}{2}),
\]

(2)

respectively, where \(\beta_p\) is the pattern speed (in the units of \(c\)) of the approaching and receding components, \(\theta\) is the angle to the line of sight and \(D\) is the distance of the source, while \(\mu_A\) and \(\mu_R\) are the proper motions of the approaching and receding components respectively. For extragalactic sources, \(D\) should be replaced by \((1 + z) D_\theta\), where \(D_\theta\) and \(z\) are the angular distance and the redshift of the source, respectively. Combining these two equations, one gets a relation for determining the distance as

\[
D = \frac{c}{2 \mu_A \mu_R} \sqrt{\frac{\beta_p^2 (\mu_A + \mu_R)^2 - (\mu_A - \mu_R)^2}{1 - \beta_p^2}}.
\]

(3)

The Doppler shifted velocity of a component is defined as

\[
v_{\text{Dop}} \equiv \frac{\lambda - \lambda_0}{\lambda_0} c,
\]

(4)

where \(\lambda\) is the wavelength measured by the observer and \(\lambda_0\) is its proper value. Applying the Doppler effect we find

\[
v_{\text{Dop}} = \frac{(1 - \beta_f \cos \theta)}{\sqrt{1 - \beta_f^2}} - 1)c,
\]

(5)

where \(\beta_f\) is the flow speed in the jets. Thus, the Doppler shifted velocities of the approaching and receding components of a twin-jet should be

\[
v_A = \frac{(1 - \beta_f \cos \theta)}{\sqrt{1 - \beta_f^2}} - 1)c \quad (\theta \leq \frac{\pi}{2}),
\]

(6)

\[
v_R = \frac{(1 + \beta_f \cos \theta)}{\sqrt{1 - \beta_f^2}} - 1)c \quad (\theta \leq \frac{\pi}{2}),
\]

(7)

respectively. It is clear that \(v_R\) must be positive, while \(v_A\) can be both positive and negative (if \(\cos \theta < (1 - \sqrt{1 - \beta^2})/\beta\), then \(\lambda > \lambda_0\), \(v_A\) is positive; if \(\cos \theta > (1 - \sqrt{1 - \beta^2})/\beta\), then \(\lambda < \lambda_0\), \(v_A\) is negative).
is negative). The above two equations lead to

$$\beta_f = \sqrt{\frac{(4c + v_A + v_R)(v_A + v_R)}{2c + v_A + v_R}}. \quad (8)$$

From (1) and (2) one has (see also Mirabel and Rodriguez 1994)

$$\beta_p \cos \theta = \frac{\mu_A - \mu_R}{\mu_A + \mu_R} \quad (\theta \leq \frac{\pi}{2}) \quad (9)$$

and from (6) and (7) one gets

$$\beta_f \cos \theta = \frac{v_R - v_A}{2c + v_A + v_R} \quad (\theta \leq \frac{\pi}{2}). \quad (10)$$

Assuming

$$\beta_p = \beta_f, \quad (11)$$

then we have

$$\frac{\mu_A - \mu_R}{\mu_A + \mu_R} = \frac{v_R - v_A}{2c + v_A + v_R}. \quad (12)$$

Combining (3) and (8) and applying (11) and (12), one finds that

$$D = \frac{c(\mu_A - \mu_R)}{\mu_A\mu_R} \sqrt{v_A v_R + cv_A + cv_R} \frac{v_A + v_R}{v_R - v_A}. \quad (13)$$

It shows, if the proper motions $\mu_A$ and $\mu_R$ and Doppler shifted velocities $v_A$ and $v_R$ of the approaching and receding components of a twin-jet are measured, then the distance of the source will be well determined. Due to its simpleness, one might desire to observe proper motions and Doppler shifted velocities of twin-jet sources and then adopt the above equation to determined the distance of the source.

As pointed out by Mirabel and Rodriguez (1994), when $\beta_p = \beta_f = \beta$, there will be only three unknown quantities $D$, $\beta$ and $\theta$, then it is only necessary to measure three out of the four possible observables $\mu_A$, $\mu_R$, $v_A$ and $v_R$, which are related by (12), suggesting that only three of them are independent. Applying (12) to (13), one can have different forms of $D$ as various functions of any three of the four observables.

For instance, if only $\mu_A$, $v_A$ and $v_R$ are measured, we simply cancel $\mu_R$ from (12) and (13) and then have

$$D = \frac{c}{\mu_A} \sqrt{v_A v_R + cv_A + cv_R} \frac{v_A + v_R}{c + v_A}, \quad (14)$$

here $\mu_A$, $v_A$ and $v_R$ are independent.
In order to investigate the feasibility of this method, we consider the effect from the uncertainties of the measured values of proper motions and Doppler shifted velocities. Let the uncertainties of $\mu_A$, $v_A$ and $v_R$ be $\Delta \mu_A$, $\Delta v_A$ and $\Delta v_R$, respectively. From equation (14) we find the relative uncertainties of $D$ caused by $\Delta \mu_A$, $\Delta v_A$ and $\Delta v_R$ are

\[
\frac{(\Delta D)_{\Delta \mu_A}}{D} = \frac{\Delta \mu_A}{\mu_A},
\]

(15)

\[
\frac{(\Delta D)_{\Delta v_A}}{D} = \left| \frac{v_A^2 - (v_A v_R + cv_A + cv_R) v_A}{2(c + v_A)(v_A v_R + cv_A + cv_R)} \right| \frac{\Delta v_A}{v_A},
\]

(16)

and

\[
\frac{(\Delta D)_{\Delta v_R}}{D} = \frac{v_A v_R + cv_R}{2(v_A v_R + cv_A + cv_R)} \frac{\Delta v_R}{v_R},
\]

(17)

respectively. The total uncertainty of $D$ is simply expressed by

\[
\Delta D = \sqrt{(\Delta D)_{\Delta \mu_A}^2 + (\Delta D)_{\Delta v_A}^2 + (\Delta D)_{\Delta v_R}^2},
\]

(18)

Equation (15) shows that, in any cases, the uncertainty of $D$ caused by $\Delta \mu_A$ is in the same order of the latter. Taking $\beta_f = \beta$ and applying (6) and (7) one finds that

\[
\frac{(\Delta D)_{\Delta v_A}}{D} = \left| \frac{\beta^2 \sin^2 \theta - (1 - \beta^2)}{2\beta^2 \sin^2 \theta (1 - \beta \cos \theta)} \right| \frac{\Delta v_A}{v_A},
\]

(19)

and

\[
\frac{(\Delta D)_{\Delta v_R}}{D} = \frac{(1 - \beta \cos \theta)(1 + \beta \cos \theta - \sqrt{1 - \beta^2})}{2\beta^2 \sin^2 \theta} \frac{\Delta v_R}{v_R},
\]

(20)

When $\beta \simeq 1$, then $(\Delta D)_{\Delta v_A}/D \simeq (1/2)\Delta v_A/v_A$ and $(\Delta D)_{\Delta v_R}/D \simeq (1/2)\Delta v_R/v_R$, showing that the uncertainty of $D$ caused by $\Delta v_A$ and $\Delta v_R$ are in the same order of them. If all the uncertainties of $\mu_A$, $v_A$ and $v_R$ are within 10%, then the uncertainty of $D$ would be well within 13%.

### 3 Discussion

In last section, we assume that the flow speed equals the pattern speed and the angles to the line of sight used in the proper motion and Doppler shifted velocity equations are the same. However, some of these assumptions may not be true. For example, from VLBI proper motion studies of extragalactic sources we know that the flow speed and the pattern speed are not always the same.

Assuming the jet and counter-jet are in opposite directions, one can determine $\beta_f$ by applying equation (8) and determine $\theta$ by

\[
\cos \theta = \frac{v_R - v_A}{\sqrt{(4c + v_A + v_R)(v_A + v_R)}} \quad (\theta \leq \frac{\pi}{2}).
\]

(21)
Meanwhile, $\beta_p$ is determined by
\begin{equation}
\beta_p = \frac{\mu_A - \mu_R}{\mu_A + \mu_R} \sqrt{(4c + v_A + v_R)(v_A + v_R)} \frac{v_R - v_A}{v_R - v_A} \tag{22}
\end{equation}
and $D$ can be determined by applying equation (13). [Combining (3) and (22) will lead to (13), suggesting that, even $\beta_p \neq \beta_f$, (13) is still valid.] It shows clearly that with the four observables $\mu_A, \mu_R, v_A$ and $v_R$ one can uniquely determine the four unknown quantities $D, \beta_p, \beta_f, \text{and } \theta$. If only three out of the four possible observables are measured and one assumes $\beta_p = \beta_f = \beta$, then $D$ can also be determined, as suggested by Mirabel and Rodriguez (1994). But if so, one might miss to observe the possible difference between the two speeds. Thus, we suggest that, if possible, all the four observables should be measured.

Many sources (both galactic and extragalactic) exhibit helical jet structure which means that the angles to the line of sight for the jet and its counter-jet are not necessarily the same. Let the angle to the line of sight for the receding component be $\pi - \theta'$, with
\begin{equation}
\theta' = \theta + \Delta \theta, \tag{23}
\end{equation}
where, $\theta$ is the angle to the line of sight for the approaching component and $\Delta \theta$ is the deviation of the angle for the receding one (which can be positive or negative). In this situation, $\theta$ in equation (2) should be replaced by $\theta'$ and the replacement would yield
\begin{equation}
D = \frac{c}{\mu_R} \frac{\beta \sin(\theta + \Delta \theta)}{1 + \beta \cos(\theta + \Delta \theta)} \quad (\theta \leq \frac{\pi}{2}). \tag{24}
\end{equation}
Taking $\Delta \theta$ as a small value, we extend this equation to the first order of $\Delta \theta$ and then get
\begin{equation}
D = \frac{c}{\mu_R} \frac{\beta \sin \theta}{1 + \beta \cos \theta} \left[1 + \frac{\beta + \cos \theta}{(1 + \beta \cos \theta) \sin \theta} \Delta \theta\right] \quad (\theta \leq \frac{\pi}{2}). \tag{25}
\end{equation}
For a twin-jet close to the plane of the sky, $\theta \simeq \pi/2$, then $(\beta + \cos \theta)/[(1 + \beta \cos \theta) \sin \theta] \simeq \beta$. It shows that if $|\Delta \theta| < 0.1$ (0.1 corresponds to $5.7^\circ$), the deviation of the distance caused by $\Delta \theta$ will be less than 10% (note that $\beta < 1$). So, for the requirement of 10% uncertainty of the distance, the deviation of the angle to the line of sight of the receding component of a twin-jet close to the plane of the sky is allowed to be $5.7^\circ$.

4 Potential observational targets

For the convenience of choosing sources to observe, we list some sources as potential targets.
(a) Sources with their proper motions available

As for recent observational targets, we preferentially suggest the following sources since their proper motions have been detected and their jets seem to be quite close to the plane of the sky.

(1) Sources in the Galaxy

GRS 1915+105 (Mirabel and Rodriguez 1994, Fender et al. 1999): \( \mu_A = 23.6 \pm 0.5 \) mas day\(^{-1} \), \( \mu_R = 10.0 \pm 0.5 \) mas day\(^{-1} \)

GRO J1655-40 (Hjellming and Rupen 1995): \( \mu_A = 54 \) mas day\(^{-1} \), \( \mu_R = 45 \) mas day\(^{-1} \)

XTE J1819-284 (Hjellming et al. 1999): \( \mu_A = 500 \) mas day\(^{-1} \), \( \mu_R = 200 \) mas day\(^{-1} \)

(2) Extragalactic sources

1146+596 (NGC 3894) (Taylor et al. 1998): \( z = 0.01085 \), \( \mu_A = 0.26 \pm 0.05 \) mas yr\(^{-1} \), \( \mu_R = 0.19 \pm 0.05 \) mas yr\(^{-1} \)

1946+708 (Taylor and Vermeulen 1997): \( z = 0.101 \), \( \mu_A = 0.117 \pm 0.020 \) mas yr\(^{-1} \), \( \mu_R = 0.053 \pm 0.020 \) mas yr\(^{-1} \)

(b) Sources with their Doppler shifted velocities available

The following sources are all inside the Galaxy. They might be chosen to observe proper motions since their Doppler shifted velocities are available.

RX J0019.8+2156 (Cowley et al. 1998): \( v_R = 712 \pm 35 \) km s\(^{-1} \), \( v_A = -690 \pm 35 \) km s\(^{-1} \)

RX J0513-69 (Southwell et al. 1996; Cowley et al. 1998): \( v_R = 4000 \) km s\(^{-1} \), \( v_A = -3700 \) km s\(^{-1} \)

CAL 83 (Crampton et al. 1987; Cowley et al. 1998): \( v_R \sim 2450 \) km s\(^{-1} \), \( v_A \sim -690 \) km s\(^{-1} \)

(c) Potential sources

Listed in the following are some potential sources probably to be interesting targets. Some of them are convinced to be twin-jet sources while others might probably possess the twin-jet structure.

(1) Potential sources in the Galaxy

XTE J0421+560 (CI Cam radio source) (Hjellming and Mioduszewski 1998; Hjellming et al. 2000): \( \mu_A = \mu_R = 26 \) mas day\(^{-1} \)

SAX J1819.3-2525 (In’t Zand et al. 2000): \( \mu_A \approx \mu_R \in [224, 806] \) mas day\(^{-1} \)

XTE J1748-288 (Rupen and Hjellming 1998; Hjellming et al. 2000): \( \mu_A + \mu_R \geq [20, 40] \) mas day\(^{-1} \)
4U 1630-47 (Hjellming et al. 2000)
XTE J1550-564 (Hjellming et al. 2000)
XTE J1739-278 (Hjellming et al. 2000)
XTE J1806-246 (Hjellming et al. 2000)
XTE J1819-245 (V4641, Sgr) (Hjellming et al. 2000)
XTE J1859+226 (Hjellming et al. 2000)
XTE J2012+381 (Hjellming et al. 2000)

(2) Potential extragalactic sources

0316+413 (NGC 1275, 3C 84) (Marr et al. 1989, Vermeulen et al. 1994): $z = 0.0172, \mu_A = 0.58$ mas yr$^{-1}$

NGC 1052 (Kellermann et al. 1999): $z = 0.0049, \mu_A + \mu_R = 1.3$ mas yr$^{-1}$

NGC 4258 (Burbidge 1995; Uzernoy 1996): $z_1 = 0.398, z_2 = 0.653$

3C 338 (Giovannini et al. 1998): $z = 0.03023, \mu_A \approx \mu_R \approx 0.30 - 0.33$ mas yr$^{-1}$

Centaurus A (Tingay et al. 1998; Dhawan et al. 1998): $\mu_A = 0.4$ mas yr$^{-1}$

5 Conclusions

In this paper, we discuss the possibility of using observational data of twin-jets to determine the distance of sources inside and outside our galaxy. It is known that Doppler shifted velocities of a twin-jet can solely determine the flow speed of components of the jet and the angle to the line of sight, while proper motions of the components can be used to determine the distance of the source when the pattern speed of the components or the angle to the line of sight is known. Therefore, one can observe proper motions as well as Doppler shifted velocities of a twin-jet and then determine the distance of the source without referring to any standard quantities such as standard candles or rods. We investigate the feasibility of this method by considering the uncertainty of the distance caused by the uncertainties of the measured values of proper motions and Doppler shifted velocities. It shows that, when the motion of the components of the jet is relativistic, then the uncertainty of the distance is within the same order of the uncertainties of the measured values of proper motions and Doppler shifted velocities. For example, when assuming the pattern speed equals the flow speed, for 10% uncertainties of the measured quantities, the uncertainty of the distance caused by them would be well within 13%.
As shown in last section, the uncertainty of proper motions measured inside the Galaxy can be as small as 2% (see the source of GRS 1915+105); that measured outside the Galaxy can be as small as 17% (see the source of 1946+708); while the uncertainty of Doppler shifted velocities measured inside the Galaxy can be as small as 5% now (see the source of RX J0019.8+2156). It is obvious that, with current technique, it is possible now to observe proper motions and Doppler shifted velocities of twin-jets and then to determine the distance of the sources within a quite satisfied order of uncertainty.

The advantage of this method is of course that it does not refer to any standard quantities such as standard candles or rods. The disadvantage is that there have been only a few twin-jet sources detected, and it is hard to measure both the proper motion and the Doppler shifted velocity of a source in the same time since the two quantities are currently observed in different wavelengths. To overcome the later disadvantage, the method used in observing NGC 4258 (Herrnstein et al. 1999) might be desired to be applied to the known twin-jet sources. If so, we will be able to determine the distance of a source with the well-defined method.

For the convenience of choosing sources to observe, some sources as potential targets are also listed in this paper. For these sources, some are known to be twin-jet ones while others might possess the twin-jet structure.

ACKNOWLEDGMENTS

We thank Max-Planck-Institut fur Radioastronomie as parts of this work were done by Dr. Yi-Ping Qin when he was a scientific guest there. Thanks are also given to Professor G. Weigelt for his helpful advice. This work was supported by the United Laboratory of Optical Astronomy and Laboratory of Cosmic Ray and High Energy Astrophysics, CAS, and the Natural Science Foundation of Yunnan.
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