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Indications for Frequency Dependent Radio Core Position in 1823+568

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Abstract

The International Celestial Reference Frame (ICRF) defining source 1823+568 was observed as a calibrator in our multi-frequency very long baseline interferometry (VLBI) experiment. Images taken at 5, 8.4, 15 and 22 GHz reveal that there is a shift in position of the source between these frequencies. The shift of the "radio core" in this object is qualitatively in agreement with predictions of conical jet models developed for radio-loud active galactic nuclei (AGN). This effect can be quite common in quasars, and "ultra-precise" astrometric projects may require a correction for it in the future.

1. Introduction

The central engine of radio-loud active galactic nuclei (AGN) is assumed to be located within a compact radio component, called the radio core. A sub-group of radio-loud AGN are core dominated quasars, where the core (i.e. location of the central engine) is routinely associated with the most compact, flat spectrum component, which is usually also the brightest one. Flat spectrum means that the observed flux density is a weak function of frequency. Core dominated quasars are subject to astrophysical studies in order to understand e.g. particle acceleration mechanisms in astrophysical jets, and are also targeted by geodetic VLBI projects.

Quasars are at huge distances from us and therefore their proper motion is practically below detection limits (but cf. Ma et al. 1998). Their radio structure is compact and simple, so they are good candidates for defining the International Celestial Reference Frame (ICRF). In this paper we present multi-frequency very long baseline interferometry (VLBI) images of one of the ICRF defining sources, 1823+568, and interpret its structure in the context of compact jets.

2. Compact Jets in Radio-loud AGN and in Microquasars

Spectral properties of VLBI cores in quasars were interpreted by the conical jet model of Blandford and Königl (1979). In this model the compact cores are in fact unresolved jets that have different radiative properties at different frequencies, but their integrated spectrum remains nearly flat. One of the consequences of this model is that the jet reaches its peak brightness at different distances from the central engine at different frequencies.

The reason for the shift of the peak brightness in the jet is local absorption of the emitted synchrotron radiation. This so-called synchrotron self-absorption is more significant closer to the central engine, and much more effective at low frequencies. Due to this effect, the low frequency VLBI core component is observed at a greater distance to the central engine, with respect to the higher frequency ones. However, as i) the central engine itself cannot be seen, ii) the positional information is lost in astrophysical VLBI experiments, and iii) the effect was assumed to

be very small, images taken at different frequencies are usually aligned by the observed radio core components.

The dependence of core position shift on physical conditions within compact jets was studied in detail by Lobanov (1998). Calculations indicated that a shift of a few tenths of a milli-arcsecond (mas) may be quite common in quasars between 5 and 22 GHz. In fact, frequency dependent position shifts of VLBI cores were observed in some quasars (see Lobanov 1998, and references therein). There are two ways of determining the core position shift: i) directly by phase-referencing to another source, or ii) indirectly, by aligning optically thin jet components. In the latter case we select a jet component observed at two (or more) frequencies. These components are in general optically thin to synchrotron radiation, i.e. absorption effects do not affect their observed position. We align the images taken at different frequencies with the help of these components, and estimate the core position shift.

The latter method was used in aligning images of the microquasar SS433 obtained at 1.6, 5 and 15 GHz (Paragi et al. 1999). In this case the shift of the core-jets was 4 mas between 1.6 and 5 GHz. The use of optically thin jet components in aligning images (instead of the brightest core-jet components, which would be located at the phase centre after the first self-calibration step at all frequencies) was checked independently by fitting the well established kinematic model to the observed radio structure. The kinematic centre (i.e. the central engine of SS433) was located in a radio quiet gap in between the approaching and receding core-jets, and the position shift of these features with frequency was confirmed.

3. The ICRF Defining Source 1823+568

The source 1823+568 is a BL Lac type object at a redshift of z=0.664 showing apparent superluminal motion (Gabuzda & Cawthorne 1996, and references therein). It has a core-jet VLBI structure with structure index of 1 in both S and X bands (Fey & Charlot 1997). The structure index may have values from 1 to 4 (with increasing structural effects), and is defined by the error delay introduced by the source structure. The error delay is below 3 picoseconds for the most compact sources. Based on its observational history, stable position and small structure index, 1823+568 was selected to be a defining source of the ICRF (Ma et al. 1998).

We observed 1823+568 with the NRAO Very Long Baseline Array (VLBA) as a calibrator source on 26 March 1998. The experiment was carried out at 5, 8.4, 15 and 22 GHz, the target source was again SS433. Initial data calibration was done in the NRAO AIPS package (Cotton 1995; Diamond 1995). We used DIFMAP (Shepherd et al. 1994) for imaging. We imaged the calibrator as well at all frequencies from the few minutes of data (5–7 minutes per frequency, each observed at three different hour angles). We were able to reconstruct the well known mas scale structure of the source at all frequencies.

We also performed model-fitting in DIFMAP. The bright jet component located at 6.56 mas distance from the VLBI core at 5 GHz, is found to have an increasing separation with frequency: 7.19, 7.35 and 8.00 mas at 8.4, 15 and 22 GHz, respectively (with an estimated accuracy of 0.1 mas). We attribute this apparent position shift to the shift of the radio core with respect to the optically thin jet component, as the theory of compact jets predicts.

Note that the measured position is very uncertain at 22 GHz, and is not in agreement with the lower frequency separation values, as the expected core position shift is proportional roughly with $(\nu_2 - \nu_1)/\nu_1\nu_2$ (Lobanov 1998). Still, there is a clear tendency of increasing component separation

with frequency. The VLBI images at 5, 8.4, 15 and 22 GHz are shown in Fig. 1. We applied the same restoring beam in all cases (2×1 mas at $PA = 0°$), and aligned the optically thin jet components in order to illustrate the VLBI core position shift.

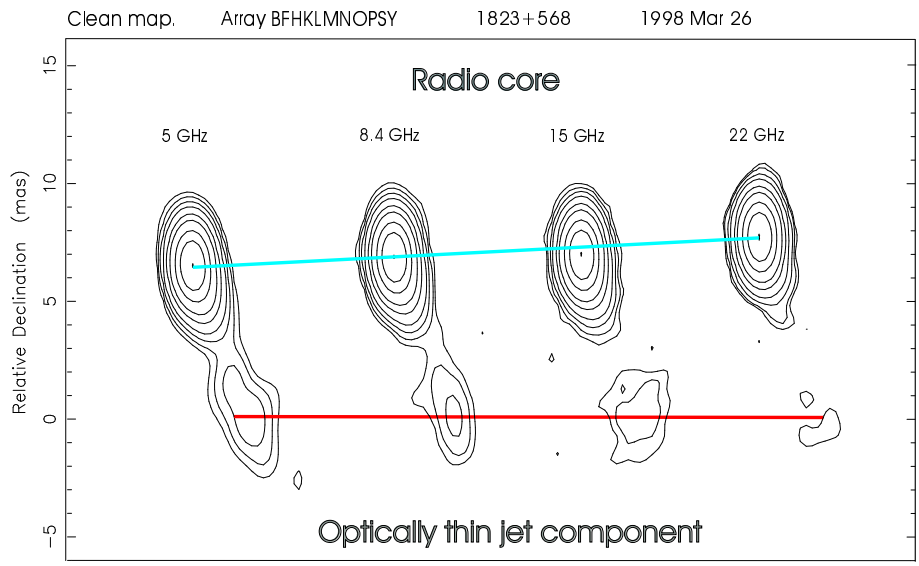

Figure 1. VLBA images of the ICRF defining source 1823+568 at 5, 8.4, 15 and 22 GHz, respectively. The restoring beam size is 2×1 mas at $PA = 0°$ in all cases. We shifted all images according to the model-fitting results, in order to align them by the optically thin jet component (assumed to be at the same physical location in the sky at all frequencies)

4. The Effect of VLBI Core Position Shift on Astrometric Analysis

The VLBI position of quasars determined by astrometry is the position of the phase centre, which is presumably located in the VLBI core (for core dominated quasars with simple structure). If source structural effects are taken into account, the measured position is that of an arbitrarily selected reference point. One way – though not necessarily the best – is to select a reference point that minimizes the calculated source structure delays. In this case the reference point is also found to be at or near the peak brightness distribution, i.e. in the radio core (Fey & Charlot 1997).

If there is a VLBI core position shift in a quasar, then the reference points selected in the S and X band images do not correspond to the same physical location in the sky. The maximum difference of the group delays measured in the S and X bands due to this effect is given by:

$$\Delta_{\rm gd}^{\rm max} = 1.6 \times 10^{-8}\,{\rm s}\,\left[\frac{B}{1000\,{\rm km}}\right]\left[\frac{\Delta r}{1\,{\rm mas}}\right]\,, \qquad (1)$$

where B is the projected length of the baseline. This difference in the group delays depends purely on the source-baseline geometry, and so will be baseline dependent.

In the process of ionospheric correction one forms a linear combination of the group delays measured in the S and X bands, in order to correct for the ionospheric delay contribution. The maximum group delay error introduced by the shift between the S and X band reference points on

a given baseline is:

$$\tau_{\rm err}^{\rm max} = 0.08\ \Delta_{\rm gd}^{\rm max}\ . \tag{2}$$

For an 8000 km baseline and 0.1 mas shift in the reference point the maximum error delay is only 1 ps, which is very small compared to the present level of accuracy. However, VLBI core position shifts as large as 1 mas (if such large shifts exist) must be accounted for in future ultra-precise astrometric analysis (cf. Charlot 1990).

Note that the separation of the VLBI core from the central engine at a given frequency depends on physical conditions within compact jets. If these change, both the position of the core at a given frequency *and* the observed position shift between two frequencies may change. As physical conditions determine the emitted radiation from the source, it follows that these position changes must be coupled by changes in the observed flux density. These effects must be studied in detail in the future.

Also note that the conical jet model cannot be applied to all sources, for example it does not apply to compact symmetric objects (CSO), and to sources that are dominated by a bright jet component that was ejected recently. Future observations are needed to establish what fraction of core-jet sources show a measurable shift of radio core position with frequency.

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