Astrometric Positions of Gravitational Lensed System 1422+231

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Abstract A gravitational lensing event can occur when a gravitational field of, e.g., a cluster of galaxies, distorts and magnifies the light from a distant, background galaxy that is almost in the same line of sight as the lensing mass. Among the ∼500 discovered gravitational lensed systems, the European Space Agency mission Gaia has detected at least one lensed image in ∼300 of these systems and released their astrometric parameters in EDR3. According to research, high accuracy VLBI observations to determine the relative positions between possible lensed images were carried out for 25 lensed systems. The lensed images refer to the various visible components in the field of view in the direction of the lensing system. Because these multiple lensed images of a source are typically a few arcseconds or less apart on the sky, they can be imaged on one map. This allows to determine the relative positions between them with an accuracy of tens of microarcseconds. This may enhance the study of the position differences between radio and optical, given that the multiple lensed images of an individual source are detected by both VLBI and Gaia. We report on the astrometric positions from historical VLBI observations, the results from the latest VLA observations, and the Gaia EDR3 results. We focus on the lensed system 1422+231, for which high-accuracy relative positions for the complete set of its lensed images are available from geodetic VLBI observations conducted in the 1990s. This study aims to understand the VLBI/Gaia position differences seen for 1422+231 and to potentially improve the modeling of the gravitationally lensed system, 1422+231, using more accurate astrometric positions from radio and optical.

Keywords 1422+231, Gaia EDR3, phase referencing, geodetic VLBI, VLA

1 Introduction

Among the ∼500 discovered gravitational lensed systems, the European Space Agency mission Gaia[1] has detected at least one component for ∼300 of these systems. According to our research, VLBI observations were carried out to determine the high accuracy relative positions between the multiple images detected in 25 systems so far. In these 25 systems, however, there are only four sources for which Gaia EDR3 has detected one image: 0218+358, 1030+074, 1152+199, and 2108+213; and only two sources with more than one image detected: 1422+231 and 0957+561. The latter two sources were popular targets in geodetic VLBI observations from ∼20 years ago, with major contributions from the Mark III system in the 1990s (Clark et al., 1985).

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[1] https://sci.esa.int/web/gaia

This source was first reported to be a gravitational lensed system, consisting of four components (denoted A, B, C, and D) with a maximum image separation of 1.3 arcseconds, by Patnaik et al. (1992) using VLA + MERLIN. The background radio source is believed to be associated with a 15.5-mag quasar at a redshift of 3.62. The optical follow-up observations made by Remy et al. (1993) found optical images for all four radio components and no other images (i.e., for the lensing source), providing further evidence to support this source to be a gravitational lensed system. Besides the relative position of these components, the authors also gave the photometric information (V, R, and i). Yee & Ellingson (1994) and Bechtold & Yee (1995) made high-resolution maps of this source and found galaxies (G) at z ~ 0.4 that are likely to be the lenses (see also, Kundicet et al. 1997; Tonry 1998).

The imaging and spectroscopic analyses given in Hammer et al. (1995) suggest that the lensing galaxy is a spiral galaxy. Impey et al. (1996) presented observations from the Hubble Space Telescope (HST) of this system and reported that the photometric properties of the lensing galaxy are consistent with an elliptical galaxy. Patnaik et al. (1999) used the VLBA and the 100-m telescope at Effelsberg to observe this system and provided new measurements of the relative positions for the components in radio. All the aforementioned publications provide astrometric information (relative or absolute) for B1422+231. Besides these observations, other authors (for example, Hogg & Blandford (1994)) constructed a theoretical model for the system. There are many studies about this system aiming to investigate why the ratio of the flux of component A over that of component B is not consistent at different frequencies. While component A is roughly as bright as component B in the radio, the optical flux of component A is only about 0.8 of that of component B. Several possible explanations were provided in, e.g., Hogg & Blandford (1994); Narasimha & Patnaik (1994); Kormann, Schneider & Bartelmann (1994); and Mao & Schneider (1998)). Polarization images were derived by Patnaik et al. (1999).

2 Astrometric Positions at Optical

High-accuracy optical positions were obtained using the sub-arcsecond imaging spectrograph of the Canada-France-Hawaii Telescope in May 1994, as listed in Table 1.

Table 1 Relative position at optical wavelengths in 1994.3 (Units: mas).

Image	r (mag)	$\Delta\alpha\cos(\delta)$ (mas)	$\Delta\delta$ (mas)
A	16.69±0.01	389 ± 3	304 ± 3
B	16.37±0.01	0 ± 3	0 ± 3
C	17.15±0.01	-337 ± 3	-755 ± 3
D	20.11±0.07	930 ± 20	-780 ± 20

The EDR3 data release provides the currently most accurate optical positions from the Gaia mission. The relative positions were calculated and listed in Table 2.

3 Astrometric Positions at Radio

The most accurate radio positions were provided by Patnaik et al. (1999) based on phase referencing observations using the VLBA and Effelsberg antennas at 8.4 GHz. The results are listed in Table 3.

By comparing Tables 2 and 3, significant changes are seen from 1997.5 at radio to 2016 at optical for the relative positions between components A and B by 12.6 mas and between components C and B by 4.0 mas.

4 Position Differences due to Relative Motions between the Images?

The relative positions of the four images of the system 1422+231 as seen by VLBI phase referencing and Gaia have differences that are far larger than their uncertainties. There are two possibilities for these differences: (1) the positions of these lensed images changed from 1997.6 to 2016; (2) there is a large difference between the optical and radio positions of the background source. In order to separate these possibilities, we analyzed the VLA observations of 1422+231 taken on 2018-02-27, to derive the relative positions of the images at a time closer to the reference epoch of the Gaia positions, as shown in Figure 1.

The parameters from model fitting in DIFMAP is shown in Table 4. These results confirm that the relative positions between these four images from 1997.5

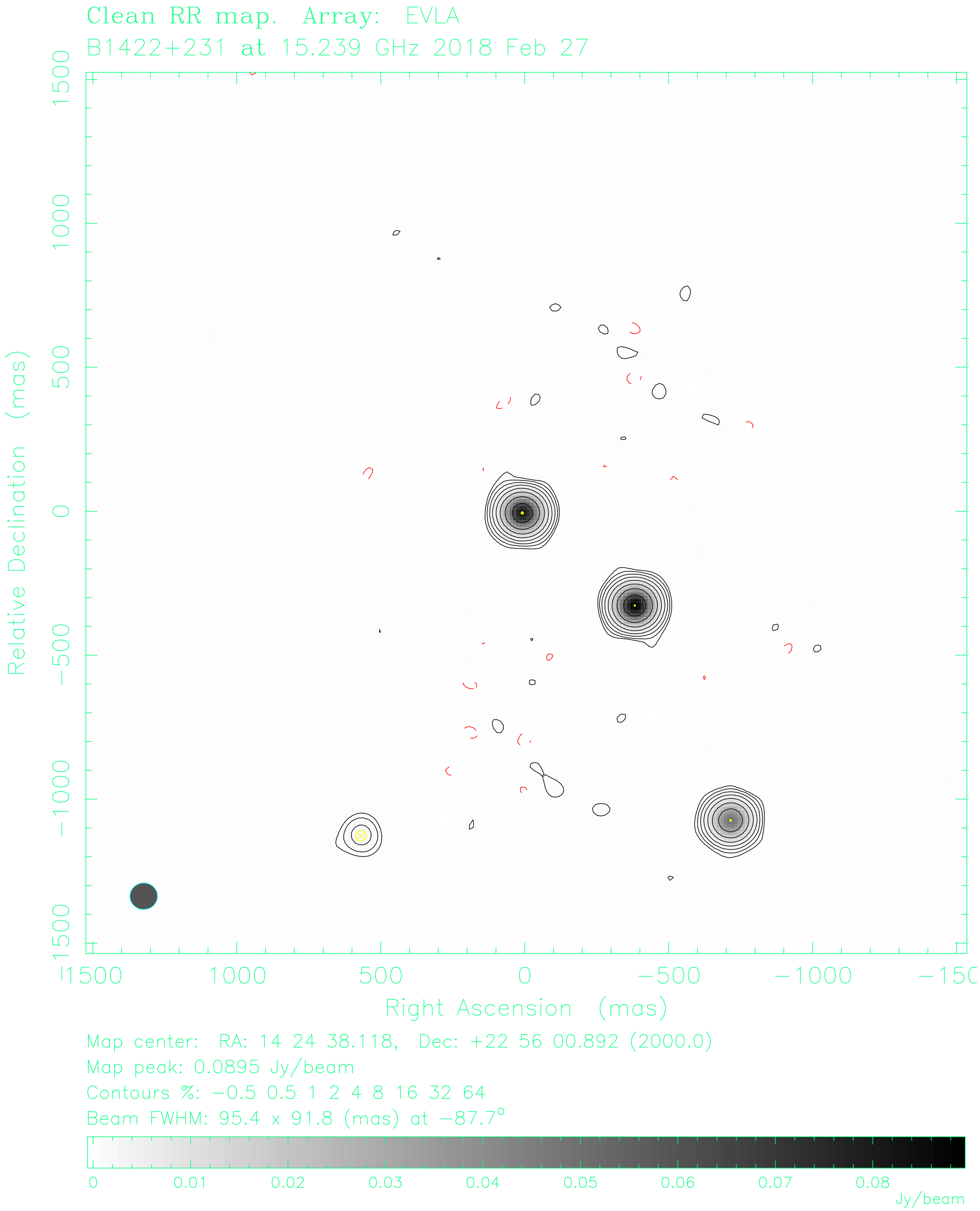

Fig. 1 VLA map of the system 1422+231 at 15.2 GHz in 2018-02-27 obtained in this work. The bottom-left component is image D, and the other three components are A, B, and C from top to bottom, respectively. Their relative positions at radio in 1997.6 are shown in Table 1, and in Table 2 at optical from Gaia in 2016. The relative positions determined from this map are shown in Table 4.

Table 2 Absolute and relative positions of the four images of the lensed system 1422+231 from Gaia EDR3 with the reference epoch of 2016.0. The relative positions derived from radio imaging observations are the arc lengths on the celestial sphere. The differential coordinates calculated from the absolute positions like Gaia EDR3 should thus be transferred to be the arc length for right ascension when they are compared to the radio results. The last two columns are the transferred relative positions from Gaia.

	Absolute position				Relative position (mas)		
Image	α	σ_α (mas)	δ	σ_δ (mas)	$\Delta\alpha$	$\Delta\alpha\cos(\delta)$	$\Delta\delta$
A	$14^h\ 24^m\ 38^s.1182088$	±0.38	$22^\circ\ 56'\ 00''.880164$	±0.43	426.6	392.9	307.5
B	$14^h\ 24^m\ 38^s.0897688$	±0.98	$22^\circ\ 56'\ 00''.572641$	±0.94	0	0	0
C	$14^h\ 24^m\ 38^s.0656072$	±0.06	$22^\circ\ 55'\ 59''.821368$	±0.06	−362.4	−333.8	−751.3
D	$14^h\ 24^m\ 38^s.1587172$	±70.6	$22^\circ\ 55'\ 59''.771852$	±46.1	1034.2	952.5	−800.8

Table 3 Relative positions of the four images of the lensed system 1422+231 from phase referencing observations in 1997.5 (Patnaik et al., 1999). The uncertainties were believed to be better than 0.1 mas.

Image	Total flux (mJy)	$\Delta\alpha\cos(\delta)$ (mas)	$\Delta\delta$ (mas)
A	152±2	389.25	319.98
B	164±2	0	0
C	81±1	−333.88	−747.71
D	5±0.5	950.65	−802.15

to 2018.1 do not change, at least at the milliarcsecond level. We may conclude that the differences in the relative positions between Patnaik et al. (1999) and Gaia EDR3 are due to the position difference of the background source between radio and optical observations.

Table 4 Relative positions of the four images of the lensed system 1422+231 from VLA observations in 2018 as determined from the map in Figure 1. Formal errors are reported by DIFMAP.

Image	Total flux (mJy)	$\Delta\alpha\cos(\delta)$ (mas)	$\Delta\delta$ (mas)
A	82.7±0.1	390.6 ± 0.06	321.1 ± 0.06
B	90.0±0.1	0 ± 0.06	0 ± 0.05
C	48.1±0.1	−333.0 ± 0.11	−746.3 ± 0.10
D	2.9±0.1	950.0 ± 2.00	−799.5 ± 1.90

5 Outlook and Future Work

The position difference of the background source between radio and optical, after being affected by gravitational lensing, shows different phenomena for the four images: the difference in the relative position is 12.6 mas for the image pair of A and B between radio and optical, and 4.0 mas for the pair of C and B. The uncertainty of the position of component D is rather large at both optical and radio. The relative positions show significant differences between optical and radio.

No significant movements among the images were detected over 20 years at optical or radio wavelengths for 1422+231. However, geodetic VLBI observations of this sources may provide additional information to validate the results.

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