VLBI phase−reference and multi−frequency observations of the gravitational lens JVAS B0218+357

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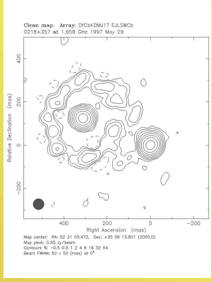
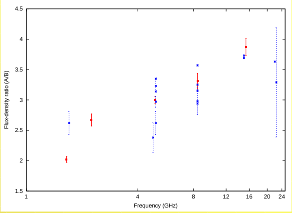
Introduction

Gravitational lenses have been a subject of great interest ever since the discovery of the first lensed system 25 years ago. The use of the radio technique, very long baseline interferometry *(VLBI)*, to study such a class of objects enhances our knowledge as a result of the phenomenal combination of the resolutions provided by both this technique and the telescopic nature of gravitational lensing that leads to the magnification of the background source.

Identified as a gravitationally lensed system in 1992 (Patnaik et al.), the radio image consists of an Einstein ring and two compact images separated by ∼ 330 mas (Figure 1). The lens is identified as a spiral galaxy ($z \sim 0.685$, O'Dea et al 1992, Browne et al. 1993) and the background source is conjectured to be a blazar ($z \sim 0.944$, Cohen et al. 2003). The latter is variable in its emission, and a time delay of (10.5 ± 0.4) days between the images has been measured (Biggs et al. 1999).



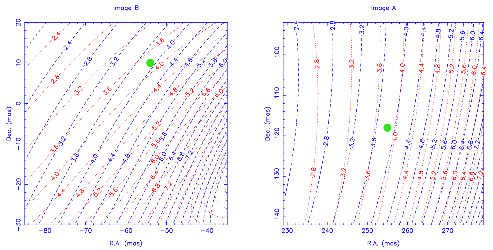
(1) A combined EVN/MERLIN 1.7 GHz map with 50 mas resolution, Patnaik et al. (unpublished). It shows an Einstein ring and the two compact images, A on the right and B on the left.



(2) Image flux-density ratios (A/B) from these observations (red symbols) and previous observations (blue symbols).

Amongst the unexplained observations, the steady and systematic drop in the image flux-density ratio with decreasing radio frequency (Figure 2) is most intriguing. One of the possible explanations is a frequency-dependent source structure, combined with an image relative magnification which changes significantly over the extent of the structure (perhaps likely, given that the system has the smallest image separation amongst the known galactic lenses). For example, in the best-fitting lens models obtained from applying the LensClean algorithm (Wucknitz 2002), a shift of ∼ 15 mas in the position of a point-source image can produce a change in relative magnification from 4 to 2.5 (Figure 3). Furthermore, it is indeed common for the radio spectra of AGN jets to steepen with distance from the central engine, and for the centroid of the brightness distribution to shift with frequency - the "core shift".

Although such a core shift should, in general, show up as a change with frequency of the separation between the two different core images, this effect is insensitive to core shifts in some directions. An unambiguous registration of the VLBI structures of the radio images at different frequencies can only be made using the technique of phase referencing.



(3) The contours of constant relative image-magnification. The lens models are singular elliptical potential with an isothermal profile (blue curves) and a non-isothermal profile (red curves). The green filled circles correspond to the peak positions of A and B at 15 GHz relative to the lens center.

Observations

VLBI observations suffer from the corrupting influence of the troposphere, ionosphere and instrumental uncertainties on the interferometer visibility phase. It is well-known that the use of phase self-calibration to eliminate these errors results in loss of the geometrical phases which contain information regarding the source position relative to the antennas, resulting in the loss of any information on the source position in the sky.

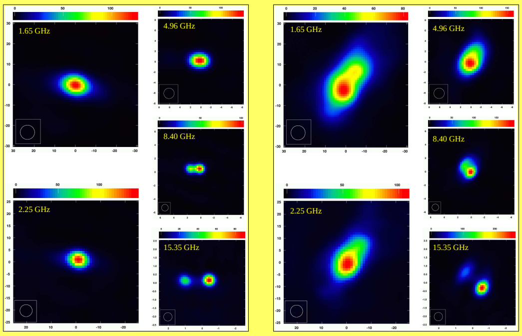
Alternatively, the technique of *phase-referencing* can be used, wherein observations of the *target* and a *reference source* are alternated frequently, allowing mapping of the target and determination of its position with respect to the reference. If the reference source is sufficiently compact that its position is achromatic, it can be considered as an astrometric calibrator. Then, the phase-reference observations can be used to make a correct registration of maps of the target source at different frequencies, to study any frequency-dependent structure.

Although this technique is most often used for mapping faint radio sources, the target in our study, B0218+357, is sufficiently strong (∼ 1 Jy) that we can use "inverse phase-referencing". Here, the lens is used as the phase-reference for determining the corrupting phases, and phase-reference maps of a point-like, achromatic astrometric reference source are made. One advantage is that relatively faint sources can be used as astrometric references, permitting the choice of sources closer to the target, which minimizes telescope drive times and reduces any difference between the tropospheric and ionospheric phase corruptions of the target and reference. Another advantage is that multiple astrometric reference sources can be used to guard against the possibility that any single one may have chromatic structure.

The observations were taken on the 13th and 14th of Jan. 2002 using the VLBA (Very Long Baseline Array) and Effelsberg (Eb) at five frequencies, namely 15.35 GHz, 8.40 GHz, 4.96 GHz, 2.25 GHz and 1.65 GHz. Apart from observing the lens, three phase-references were observed along with a fringe detector. The data was correlated at the VLBA correlator and further processed in AIPS.

Maps of B0218+357

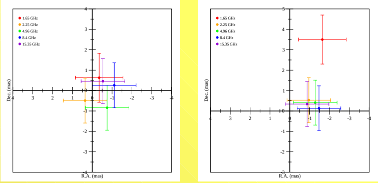
Hybrid maps (using phase self-calibration techniques) of the lens were made by cleaning two sub-fields containing the two images A and B, simultaneously. The images clearly manifest all the earlier observed characteristics due to lensing, such as image A being tangentially stretched at a position angle of $\sim -40^\circ$ (Figure 4). At 8.4 GHz and higher frequencies, the images are resolved further into two sub-components, separated by about 1.4 mas, representing the jet-core morphology of the background source.



(4) Hybrid-maps of B0218+357 at five frequencies, image B (left) and image A (right). The color wedge at the top of each panel indicates the range of image intensity in units of mJy beam^{-1}.

Phase-Referencing

For the phase-reference analysis only one of the observed astrometric sources, 0215+364, was chosen as the most appropriate phase-reference because of its flat spectrum in comparison with the others, permitting an unambiguous registration of the brightest component at all the frequencies. The hybrid maps of the images A and B were used to investigate the change in their centroid-positions with respect to 0215+364 as a function of frequency. Figure 5 indicates a relative shift of about ≤ 3.5 mas in the centroid of image-A radio between 15.35 GHz and 1.65 GHz. For image B, on the contrary, there is no shift detected. Even though, this shift in image A can account for a 10 % change in the observed image flux-density ratio assuming a true ratio of 4, the direction of the shift coincides with that of the constant relative magnification contours. In reality, therefore, the relative image-magnification at the 1.65 GHz centroid-position corresponds to a ≤ 1 % change in the observed ratio.



(5) The left panel shows the change in the centroid position with varying frequency in image B, relative to the phase-reference B0215+364. The right panel shows the same for image A.

Discussion

The technique of inverse phase-referencing was successfully used to investigate the frequency-dependence of the emission from the images of B0218+357; this is the first time in which a gravitational lens has been used as a phase-reference. The identification of a distinct secondary maximum in image A at low frequencies (component 3, the north-west shoulder at 1.65 GHz in Figure 4), the sharp downturn in the spectrum of image A at 1.65 GHz (not visible in image B) and the small shift in the 1.65 GHz peak position in A are further results from these observations with no obvious explanation in terms of the expected magnification gradients across the images. From the phase-referenced results we conclude that the magnification gradient in the image plane, combined with the frequency-dependent source structure is not the main cause behind the flux ratio anomaly in B0218+357. It may, therefore, be necessary to consider more elaborate mechanisms, such as mass sub-structure (milli-lensing), free-free absorption or refractive scattering in the lens galaxy, to account for all the observed features in the B0218+357 images. Milli-lensing can produce significant frequency-dependent changes in the flux-density of one (or both) of the images provided the source size is comparable to the Einstein radius of the perturber and changes appreciably with frequency relative to it. The source size changes by a factor 30 over the observed frequency range and its interaction with the caustics of the perturber can bring about frequency-dependent changes in the total magnification. Electromagnetic effects such as free-free absorption or scattering will introduce flux-density perturbations that have an inverse frequency-squared dependence.

Acknowledgments:

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