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VLA and ALMA observations of the lensed radio-quiet quasar SDSS J0924+0219: a molecular structure in a 3 μJy radio source

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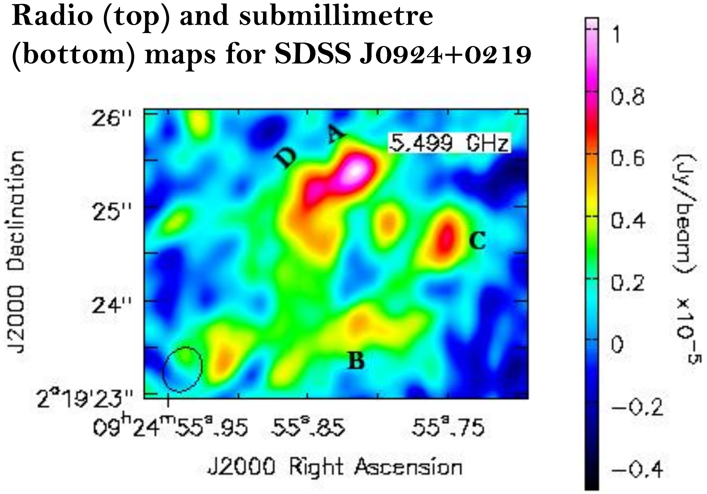
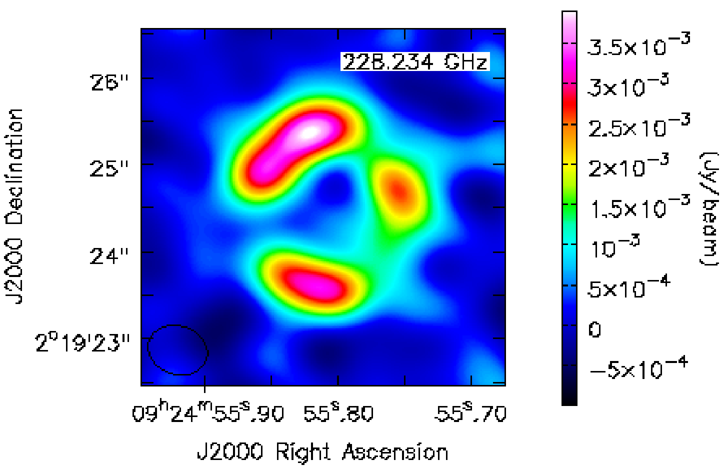
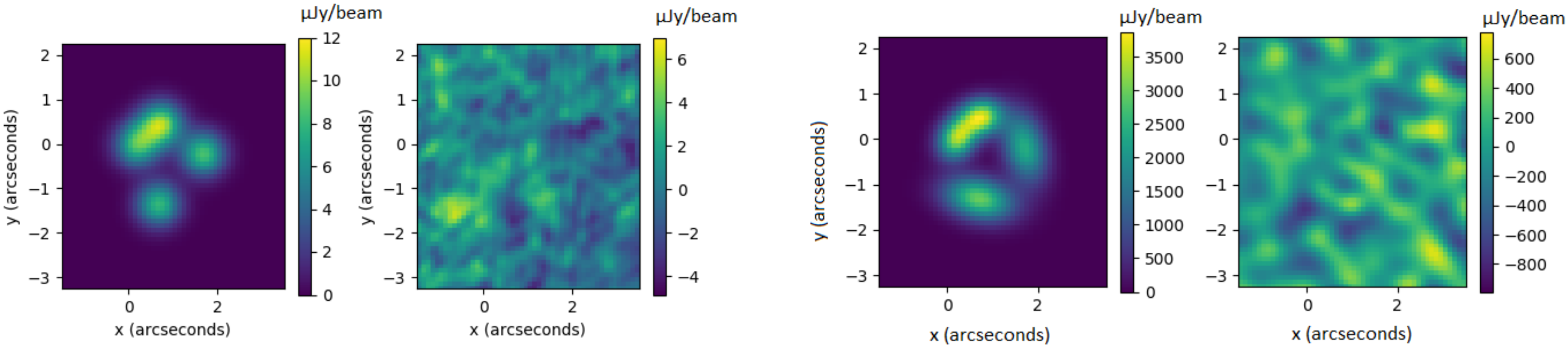
Radio (top) and submillimetre (bottom) maps for SDSS J0924+0219





Introduction

In a strong gravitational lensing system, the light from a background source is deflected due to the gravitational potential of a foreground galaxy or galaxy cluster, resulting in multiple images of the background source. The position and brightness of the lensed images contain information about the structure of the source, together with the mass distribution of the lensing galaxy (Treu 2010). Lensing galaxies or galaxy clusters also magnify the sources by factors of typically 10–20, allowing us to study lensed sources which would otherwise be unobservably faint. In a so-called 'fold lensing system', a closed curve called 'fold caustic' typically separates regions in which the source is doubly and quadruply imaged. In fold systems like SDSS J0924+0219, the closest images, theoretically, should have equal flux brightness; deviations from this may indicate millilensing by clumped matter distributions in the lensing galaxy close to the line of sight to one or both of the images, or microlensing by stars in the lensing galaxy. Multi-wavelength observations can give an insight into the reason behind the flux anomaly, as optical sources are affected by both milli- and microlensing, but radio and submillimetre sources are largely immune to microlensing effects. SDSS J0924+0219 is an intriguing source because it shows the most extreme anomaly observed in lensed systems; the flux ratio between the merging images is found to be approximately 12 in the optical. The aim of this research is to study the lensed quasar in the radio and submillimetre wavelengths and determine the flux ratios in both, giving possible clues into the reason behind the flux anomaly.



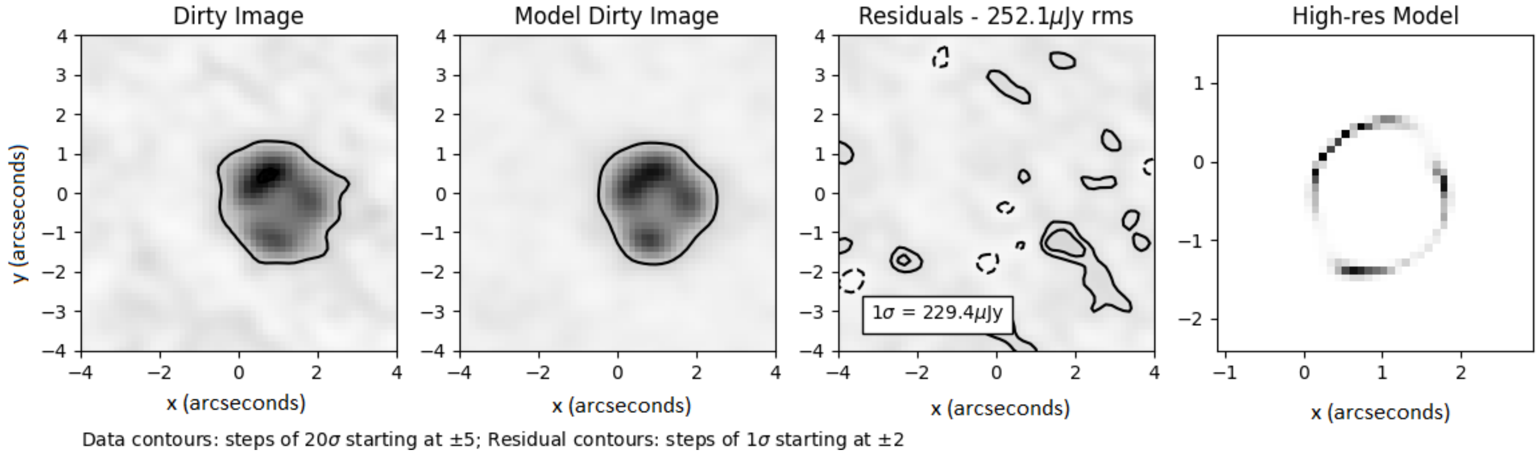
Best fit image and the corresponding residual map obtained by fitting 4 elliptical Gaussians to the 4 image positions for the radio (left) and submillimetre (right) map

Analysis and results

The beam of the 'original' VLA (radio) image was convolved to match that of the ALMA (submillimetre, CO(5-4) line) image, for the purpose of comparison. We fit four elliptical Gaussians at the positions of the images in each of the maps, an approach that makes no assumption about the detail of the lens model, in particular, its substructure content. The fit used 10 image parameters, namely the peak flux densities of the four components, the FWHMs and the axis ratios of images A and B and two overall positional offsets in the x and y directions respectively to allow for astrometric differences in the radio and optical images. The best fits yielded flux ratios equal to **1.07** (ALMA) and **1.25** (VLA). We used the best fits from this image-plane analysis as the starting points for fitting the Gaussians on the u-v plane using UVMULTIFIT (Martí-Vidal et al. 2014). The resulting flux ratios were found to be **1.58±0.15** for the ALMA map, and **1.28 ± 0.41** for the VLA map.

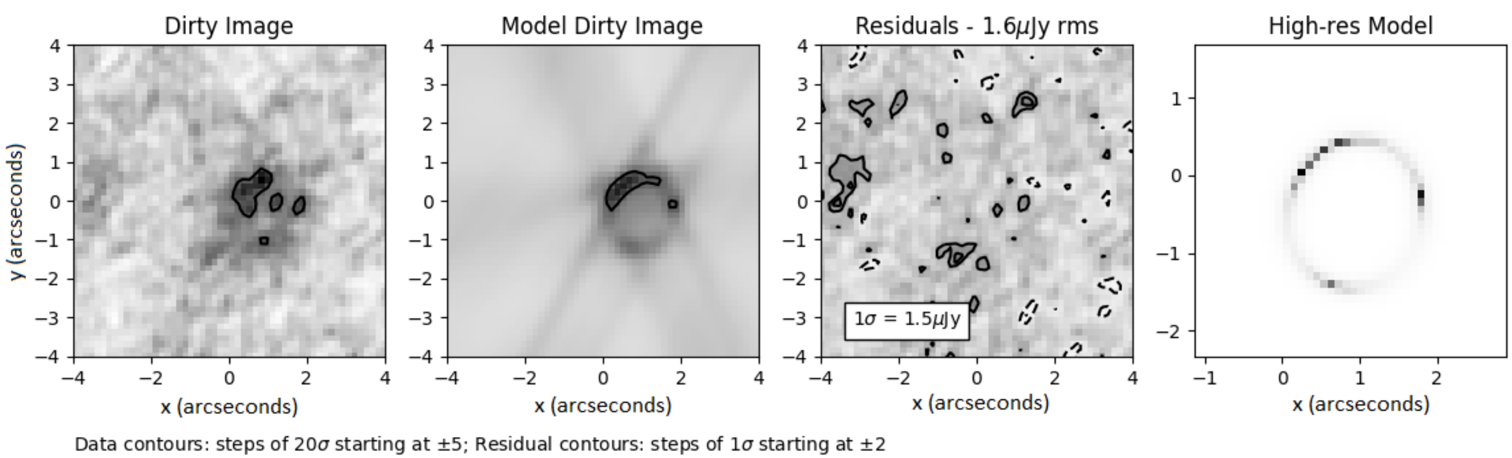
We also performed a gravitational lens modelling using the Singular Isothermal Ellipsoid (SIE) model developed by Eigenbrod et al. (2006) for the lensing galaxy. Allowing the source to have a Gaussian profile, the galaxy position and the source parameters were optimized using the difference between the data and the lensed images convolved with the point spread function. Again, the best fit parameters from this image plane analysis were used as starting points for fitting the lens model in the u-v plane using VISILENS (Hezaveh et al. 2013b; Spilker et al. 2016). The lens model fitting demonstrated that the SIE model we used clearly reproduces the main features of the data and is compatible with an extended source, together with no requirement for additional perturbations due to millilensing by substructure.

Best fit model obtained by fitting the Eigenbrod et al. (2006) SIE model to the visibility data of the CO emission line (right) and the radio (below), obtained using VISILENS.



We also used the lens model to project the frequency planes of the ALMA data back into the source plane and determined simple parameters, such as size of the emitting structure. It appears from the ALMA CO(5-4) observation that we could be seeing a structure in ordered motion, the natural explanation of which is the presence of a rotating molecular disk. The structure is of physical dimension approximately 100–300 mas (~ 850–2500 pc), consistent with a compact star-forming disk in the centre of the host galaxy of the quasar. It is also consistent with the size of the source determined from the lens model.

The flux ratio measurements demonstrate that the optical flux anomaly can be attributed to microlensing, a conclusion which is also compatible with previous studies of this object (Keeton et al. 2006; Morgan et al. 2006).



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