Using VLBI Data to Investigate the Galaxy Structure in the Gravitationally Lensed System B1422+231

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Abstract. Gravitationally lensed systems with multiply imaged quasars are an excellent tool for studying the properties of distant galaxies. In particular, they provide the most accurate mass measures for the lensing galaxy. The system B1422+231 is a well studied example of a quadruply imaged quasar, with high-quality VLBI data available. Very accurate data on image positions, fluxes and deconvolved image sizes provide good constraints for lensing models. We discuss here the failure of smooth models in fitting the data. Since the mass of a lens galaxy is not a smooth entity, we have investigated how deviation from a smooth model can influence lensing phenomena, especially the image flux ratios. To explore expectations about the level of substructure in galaxies and its influence on strong lensing, N-body simulations of a model galaxy are employed. By using the mass distribution of this model galaxy as a lens, synthetic data sets of different four image system configurations are generated. Their analysis can possibly provide evidence for the presence and strong influence of substructure in the primary lens galaxy.

1. The mystery of B1422+231

The gravitational lens system B1422+231 was discovered in the course of the JVAS survey (Jodrell Bank – VLA Astrometric Survey) by Patnaik et al. (1992). It consists of four image components. The three brightest images A, B, and C (as designated by Patnaik et al. 1992) are fairly collinear. The radio flux ratio between images A and B is approximately 0.9, while image C is fainter (flux ratio C to B is approximately 0.5). Image D is further away and is much fainter than the other images (with flux ratio D:B of 0.03). We used the most recent available radio data for the image positions and fluxes from the polarisation observations made at 8.4 GHz using the VLBA and the 100m telescope at Effelsberg (Patnaik et al. 1999). For each of the components, the authors measured positions (relative to the image B) and fluxes as well as the deconvolved image shapes.

The radio source of this lens system is associated with a 15.5 mag quasar at a redshift of 3.62 (Patnaik et al. 1992). The lensing galaxy has been observed in the optical; its redshift has been determined to be 0.338 and its position relative to image B has been measured (Impey et al. 1996). The main lens galaxy is a member of a compact group with a median projected radius of 35 h^{-1} kpc and velocity dispersion of ~ 550 km s^{-1} (Kundic et al. 1997).

Several groups have tried to model B1422+231 (Hogg & Blandford 1994; Kormann et al. 1994; Keeton et al. 1997; Mao & Schneider 1998) and all of them have experienced difficulties in fitting the image parameters. As we used data with even more precise image positions one might expect that it would become even harder to model the system. However, as already pointed out by some authors, the difficulties do not lie in fitting the image positions but rather in the flux ratios. All the results can be found in detail in Bradač et al. (2002)

2. Lens modelling with smooth models

First we considered two standard gravitational lens models. We used a singular isothermal ellipsoid with external shear from Kormann et al. (1994) (hereafter SIE+SH) and a non-singular isothermal ellipsoid model with external shear (NIE+SH) from Keeton & Kochanek (1998) to fit the image positions and fluxes of B1422+231.

We have applied the standard χ^2 minimisation procedure to the radio data, using image positions, fluxes, and their uncertainties from Patnaik et al. (1999). The optical position of the galaxy was taken from Impey et al. (1996). Although the image positions are very accurate (uncertainties of the order of 50 μarcsec), we have no difficulties fitting them. However, as already pointed out in previous works on B1422+231, such models completely fail in predicting the image fluxes. In particular image A is predicted too dim (the flux ratio A:B as predicted by SIE+SH model is 0.80, much below the measured value of 0.93). We have also tried to model the system with a NIE+SH model; however, the χ^2 did not improve significantly.

Although other smooth models can still be investigated, it seems unlikely that another smooth model can explain all four image fluxes simultaneously. Even when one disregards the flux of image A, a smooth macro-model seems to be incapable of explaining the remaining flux ratios.

3. Models with substructure

The A:B flux ratio causes the biggest difficulty in fitting B1422+231. Since the radio and optical flux ratios are very different, one is tempted to exclude it from the χ^2 measure.

However, one can also try to deal with this problem in another way. Adding a small perturber at the same angular diameter distance as the primary lens and at approximately the same position as image A can change the flux ratio A:B substantially. On the other hand, calculations show (Mao & Schneider 1998) that such a perturber does not affect the positions of any of the images appreciably. Furthermore, a small perturber can also change the flux ratio of the other images slightly and this might help to improve the results from the previous section.

We model the perturber as a non-singular isothermal sphere. We are aware of the fact that the choice of this particular model for the substructure is oversimplified in many ways. However, we are not trying to constrain the nature of substructure in this case, which is impossible due to the number of constraints available.

The resulting model has 12 parameters, which leaves us 0 degrees of freedom. For a model with zero degrees of freedom we expect χ^2 to vanish if the model is realistic. The resulting $\chi^2 = 5.6$ remained high; this family of models considered does not seem to be adequate for the description of the galaxy in B1422+231 lens system.
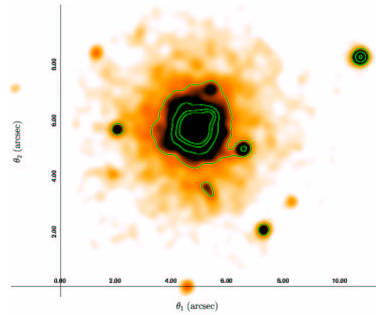
4. Using image shapes as constraints

For the more sophisticated models it is very difficult to ensure a constrained model that accounts for the substructure using as constraints only image positions, flux ratios, and the galaxy position. For this reason we also included the axis ratios and orientation angles of the deconvolved images from Patnaik et al. (1999) as additional constraints.

It turned out that it is difficult to simultaneously stretch and rotate the images with one (or two) perturber(s). The macro-model is not very successful in predicting both components of the image ellipticities and the fluxes, and therefore corrections are needed in the case of all four images. We can safely assume that the inclusion of further sub-clumps in the model would eventually lead to a "perfect" fit with the observed data. In particular three more sub-clumps close to the images B, C, and D would yield a significant improvement to the χ^2 and could explain the observed data.

5. Strong lensing by an N-body simulated galaxy

A question that arises from (difficulties in) model fitting of B1422+231 is whether such behaviour is seen with an N-body simulated galaxy and therefore generic of a typical galaxy lens. We used the cosmological N-body simulation data including gas dynamics and star formation of Steinmetz & Navarro (2001) for this purpose.

Fig. 1. The cutout of the surface mass density map of the simulated galaxy.

The lens properties are calculated using the IMCAT software. We use this "lens" to generate systems that have similar configuration and flux ratios as in the case of B1422+231. In total we considered 11 different synthetic systems.

The fitting procedure is performed in the same way as for the B1422+231 data. Again, image B is taken as a reference. We try to fit the positions and fluxes with SIE+SH and SIE+SH+NIS models. We experience similar problems fitting fluxes as before; the χ^2-function value is high for all 11 data sets.

There are indications that the level of substructure as obtained from simulations can influence lensing phenomena a lot. In particular, the synthetic fluxes we obtained deviate strongly from those predicted by smooth models. This particular example of a simulated galaxy can of course not give us the answers to the aforementioned questions. To draw stronger conclusions, one would have to investigate many different realisations of N-body simulated galaxies and in addition use higher resolution simulations (currently unavailable). A statistical analysis to investigate the strong lensing properties could then be made.

References

Bradač, M., Schneider, P., Steinmetz, M., et al. 2002, A&A accepted

Hogg, D. & Blandford, R. 1994, MNRAS, 268, 889

Impey, C., Foltz, C., Petry, C., Browne, I., & Patnaik, A. 1996, ApJ, 462, L53

Keeton, C. & Kochanek, C. 1998, ApJ, 495, 157

Keeton, C., Kochanek, C., & Seljak, U. 1997, ApJ, 482, 604

Kormann, R., Schneider, P., & Bartelmann, M. 1994, A&A, 286, 357

Kundic, T., Hogg, D., Blandford, R., et al. 1997, AJ, 114, 2276

Mao, S. & Schneider, P. 1998, MNRAS, 295, 587

Patnaik, A., Browne, I., Walsh, D., Chaffee, F., & Foltz, C. 1992, MNRAS, 259, 1P

Patnaik, A., Kemball, A., Porcas, R., & Garrett, M. 1999, MNRAS, 307, L1

Steinmetz, M. & Navarro, J. 2002, NewA, 7, 155