J. Astrophys. Astr. (2002) **23,** 115–118

CLASS B $1359 + 154$: Modelling Lensing by a Group of Galaxies

Sunita Nair *Raman Research Institute, Bangalore 560 080, India*

Abstract. The recently discovered gravitationally lensed system CLASS B1359 + 154 appears to have six detectable images of a single background source at a redshift of 3.235. A group of galaxies acts as the lens, at a redshift of ~ 1. The present work identifies two distinct, physically plausible image configurations, a 7-image one and a 9-image one. Mass models are constructed corresponding to realizations of these two configurations. Both models call for, in addition to non-singular galaxy-type lenses, a larger scale mass component that resembles the extended dark matter distributions seen in relatively low-redshift galaxy groups. It is presently observationally impossible to study the extended X-ray emission from a group at such a high redshift, hence lensing studies are of some interest. A lensed system with a high image multiplicity does not necessarily admit of a unique lensing interpretation; discrimination is possible with additional observable details (e.g., the image parities, which are uncommon among even the simpler systems).

Key words. Gravitational lensing: multiple-imaging—individual systems: CLASS B1359 + 154—galaxy groups—dark matter.

1. Introduction

A find of the Cosmic Lens All-Sky Survey (CLASS; Myers *et al.* 1995), the radio lensed system B1359 + 154 was at first identified as a quadruply-imaged ('quad') system (Myers *et al.* 1999), although six compact radio features had been detected in a deep VLA observation at 8.46 GHz. The six radio components, denoted by letters A–F (starting from North, and labelled clockwise), have flat radio spectral indices ($\alpha_{1.7\,GHz}^{5\,GHz} \sim -0.23$ to -0.38, where $f_\nu \sim \alpha^\nu$; Rusin *et al.* 2001). Images A–D are arranged in what appears to be a typical quad configuration on a scale of $1''.7$, and E and F lie within this quad. The source that is multiply imaged has a spectroscopic redshift of $z = 3.235$ (Myers *et al.* 1999). The associated lens is a group of galaxies at an estimated redshift of 1 (Rusin *et al.* 2000), with three galaxies of similar luminosities within the circle of images and three more within $10''$ of the images, in a K-band observation.

2. The image configuration in B1359 + 154

Theoretically, it is possible to construct a variety of multiple image configurations. These are characterised by the form of the 'crossing contours', or those isochrones that self-intersect, among all the isochrones that describe the arrival time surface (written

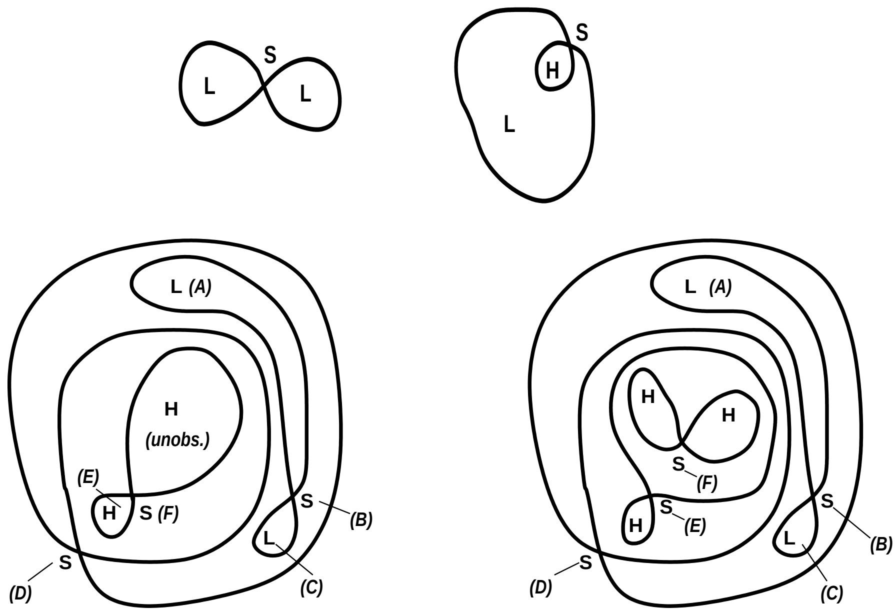

Figure 1. **(Top)**: Lemniscate (**left**) and limaçon (**right**), the three-image configuration building blocks of higher image multiplicity systems. **(Bottom)**: 7-image configuration for B1359 + 154, with one 'core-captured' demagnified H-type image (**left**), and 9-image configuration with three demagnified images (**right**).

Figure 2. Elementary 2-lens realization for the 6 images in B1359+154. (**Left**): Image plane critical curves with simulated images (contoured ellipses). Image magnification is proportional to the area enclosed by the ellipse. (**Right**): Source plane caustics, with source position marked by an asterisk.

as a function of possible image position, a two-dimensional vector in the plane of the sky) for light travelling from a distant source to the observer, and intercepted by a gravitational lens (Blandford & Narayan 1986). The crossing contours are either lemniscates or limaçons (for three-image configurations), or combinations of the two (for higher image multiplicities); see Fig. 1 (top). Applying Fermat's Principle to the arrival time functional yields the number and location of the images in terms of image coordinates, and these appear at the mimima (L in Fig. 1 (top)), maxima (H) and saddle-points (S) of the arrival time surface.

The image configuration in B1359 + 154 is conceivably either a 7-image one (with one image demagnified) or a 9-image one (with three undetectable images), or, with lesser likelihood, one of even higher multiplicity and with more demagnified images. Realistic 7- and 9-image scenarios are illustrated in Fig. 1 – though it is possible to construct 25 and 111 distinct 7- and 9-image combinations out of limaçons and lemniscates, physical arguments can be employed in order to whittle down the candidates to these two. The 7-image one is a perturbation of the typical 5-image configuration obtained with an elliptical lensing potential. It can be readily obtained, for example (see Fig. 2), with the help of a non-singular elliptical lens combined with an off-centred non-singular circular (or favourably aligned elliptical) perturber lens; that such configurations are not observed oftener is perhaps because the central distinguishing images are faint and the observable images resemble a typical ‘quad’. This 7-image configuration can also be obtained with the three observed group-member galaxies proximal to the lensed images, plus some dark matter. The 9-image configuration is motivated by the presence of the three lens galaxies nearest to the images; if each lens galaxy’s mass distribution is sufficiently centrally condensed, each will harbour a demagnified ‘central’ image, so that there must be a total of 6 (visible) plus 3 (invisible) = 9 images. This too is realizable with a lens of three galaxies plus some dark matter. (Rusin *et al.* (2001) also chance upon this latter configuration, but use 3 singular lenses; the present models use non-singular lens mass distributions).

3. Realistic mass models

Realizations (Figs. 3 and 4) of the two image configurations discussed in the previous section are constructed by prescribing the lens centres for the galaxies, image positions

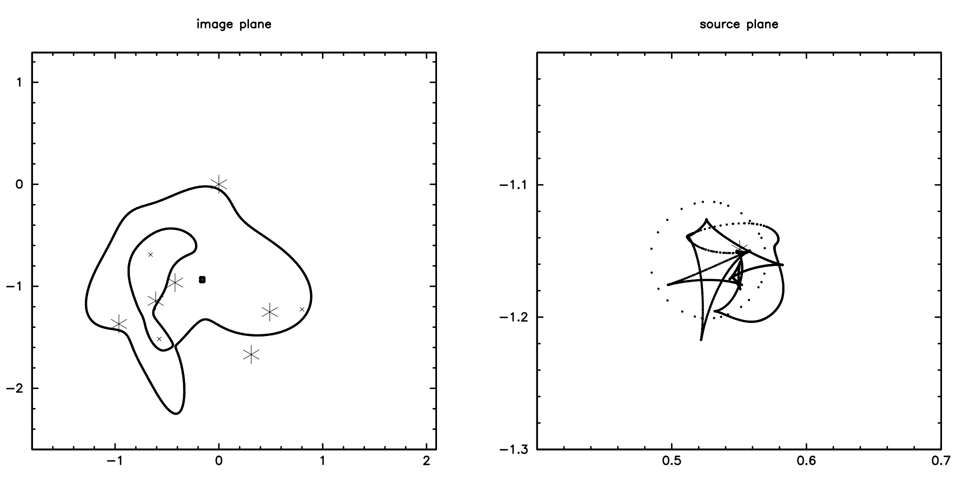

Figure 3. Model for the 7-image configuration (**Left**): Image plane critical curves; image locations are marked by asterisks, and lens centres by small crosses. The centre of the dark matter distribution is at (0.″80, −1.″23), to the west of the images. The demagnified image is near the centre of the westernmost lens galaxy at (−0.″14, −0″94). Note RA is reversed in the plots. Centre of coordinates is northernmost image A. (**Right**): The source plane caustics; the source is at the asterisk.

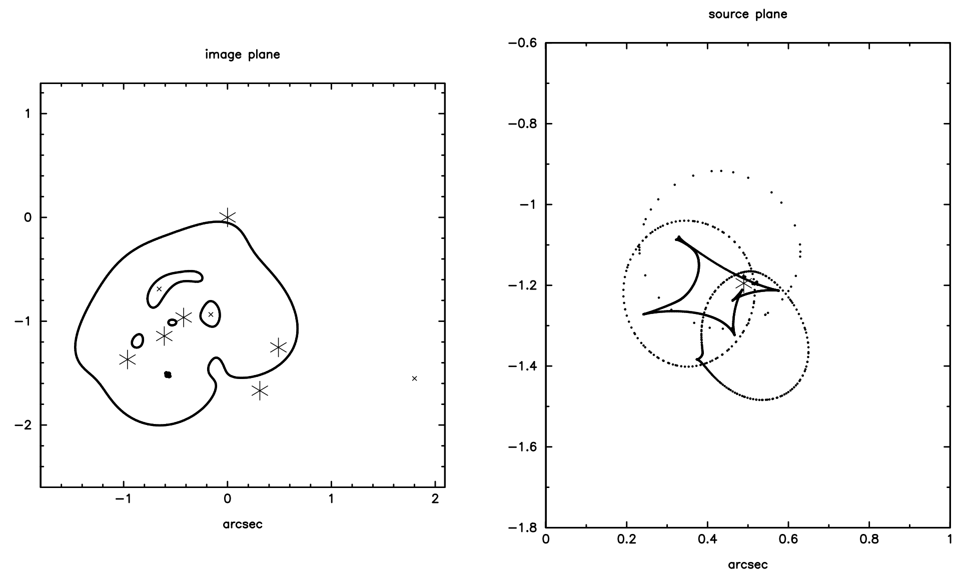

Figure 4. Model for the 9-image configuration. Details are as in previous figure, with 3 demagnified images, each proximal to one of the 3 galaxy lenses' centres. The centre of the dark matter distribution is at (1.″80, −1.″55), again to the west of the image system.

and relative magnifications (from VLBA 1.7 GHz data of Rusin *et al.* 2001), and the desired image parities. The dark matter location, velocity dispersion and scale (non-singular isothermal sphere model) are determined by modelling. Scale lengths for the dark matter distribution are 2.″5 and 1.″7 for the 7- and 9-image configurations respectively, both centred within the region bounded by the six infrared lens galaxies of Rusin *et al.* (2000).

References

Blandford, R. D., Narayan, R. 1986, *Ap. J.*, **321,** 658.
Myers, S. T. *et al.* 1995, *Ap. J.*, **447,** L5.
Myers, S. T. *et al.* 1999, *A. J.*, **117,** 2565.
Rusin, D. *et al.* 2000, *Ap. J.*, **533,** L89.
Rusin, D. *et al.* 2001, *Ap. J.*, **557,** 594.