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A gravitational lens probe of galaxy-scale dark matter ?

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Abstract. We present a model for an observed gravitationally lensed system, MG2016+112. We assume that there are two galaxies acting as lenses (as suggested by the observations), each with a diffuse dark matter halo. It is shown that the two lenses, acting in tandem, can conspire to produce the image configurations observed on both arcsecond and milliarcsecond scales. The dark matter halos, each of which is a weak lens, overlap in projection. This increases the strength of the lens system, making MG2016+112 a potential probe of diffuse dark matter in galaxies. It is possible to account for some additional, rather puzzling observations. We show, finally, that the galaxy-plus-halo structures that are suggested by our model are consistent with observations of single lens galaxy-scale systems.

Key words : gravitational lensing—galaxy—dark matter

1. Introduction

The gravitational bending of light by a foreground galaxy, which may act as a nonlinear lens for a distant quasar, can result in the production of multiple images of the source. Observed cases of lensing by isolated galaxies typically probe the projected lens mass within ~10 kpc of the lens centre, where luminous matter dominates the lensing. The overall lensing statistics for galaxies suggest, however, that dark halos may exist in galaxies (Maoz & Rix 1993). We study a lensed system that involves two lensing galaxies instead of one; in projection, the halos of these galaxies can overlap and result in an increase in the strength of the lens. The system that we model is the candidate lensed system MG2016+112 A,B,C, the only one presently thought to involve two lenses.

2. Observational overview

MG2016+112 has been the subject of extensive observations (Lawrence *et al.* 1984; Lawrence *et al.* 1993, and references therein). It has been studied in the radio (including VLBI), optical and infrared. Two objects, A and B, are quasar images sharing an identical emission line redshift of 3.273, line profiles, optical colours and radio spectral indices. They are separated by 3.″4. A third quasar image, C′, was identified through Lyman α emission at a redshift of 3.273. It is almost coincident with object C, the strongest radio source in the field, which is unusually red and has an extended structure (redshift unknown). Object D is a radio-quiet giant elliptical galaxy ($z = 1.01$). Its i-band luminosity is typical of brightest cluster galaxies, but no cluster has been detected.

A summary of the ratios of the measured fluxes between the images A, B and C′ (the flux of which is generally indistinguishable from C), is given in table 1.

Table 1. Flux ratios for the images in 2016+112

Image ratio	Radio 5 GHz	Radio VLBI	Ly-α (5180 Å)	K-band	i-band	r-band	g-band
A/B	0.94	0.95	1.63	0.77	1.33	1.16	1.41
(C + C′)/B	2.93	0.26	0.28	1.73	0.47	0.28	0.30

3. The lens model

Previous models for this system (Narasimha *et al.* 1987; Narasimha & Chitre 1989) have indicated a need for matter in excess of that which may reasonably be associated with objects C and D, and on a scale that is extended compared to either galaxy. No completely satisfactory model of this system exists to date. We model the lens galaxies as parametrized oblate spheroids, each with a similar but larger scale length mass distribution for a dark halo. The mass density distribution yields the modified Hubble profile in projection. The modelling techniques and computer programs are versions of the ones described in Narasimha *et al.* (1982, 1984). The problem actually involves 15 active parameters as opposed to eight constraints; the model we obtain is not unique, but consistent with the observations. We discuss several illuminating, if somewhat qualitative aspects of the model.

Table 2 displays the lens parameters for the lenses at C and D. The configuration is a five-image one, but it cannot be obtained with a single galaxy. Two images are core-captured and demagnified below observable levels by the centres of the lenses at C and D. Image C′ is formed ~0.2″ away from galaxy C (within the observational uncertainties). Figure 1(a) shows the source, along with the source plane caustics for this system. The images and the image plane critical curves are shown in figure 1(b). It must be mentioned that to obtain this configuration requires some lens matter which is distributed on a scale that is considerably larger than that of the image splitting.

Table 2. Lens parameters

Lens parameters	Lens at C		Lens at D	
	Galaxy C	Halo C	Galaxy D	Halo D
Velocity dispersion (km/s)	190.0	312.0	278.0	324.0
Core radius (kpc)	0.90	45.0	3.3	22.0
Cutoff (core radii)	10.0	3.0	10.0	5.0
Eccentricity	0.86	0.74	0.86	0.80
P.A. (degrees)	115	115	125	125
Centre (asec)	(0.0, 0.0)	(0.0, 0.0)	(0.37, 1.41)	(0.37, 1.41)
Redshift	0.85		1.01	

The unusual role of the lens at C : A dual role is played by the lens at C in this model. The observed relative VLBI orientations in the principal images A and B imply that the

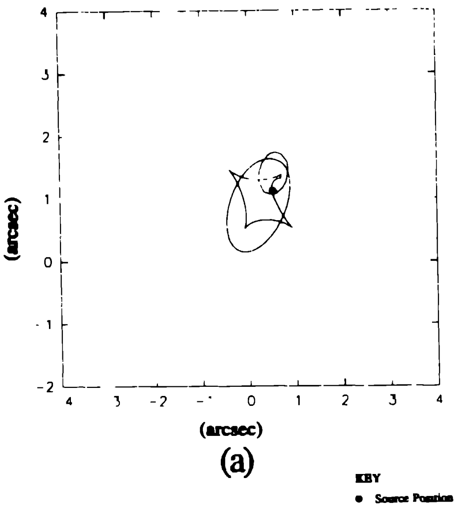


Figure 1(a). The disposition of the source (black dot) with respect to the source plane caustics for the present model.

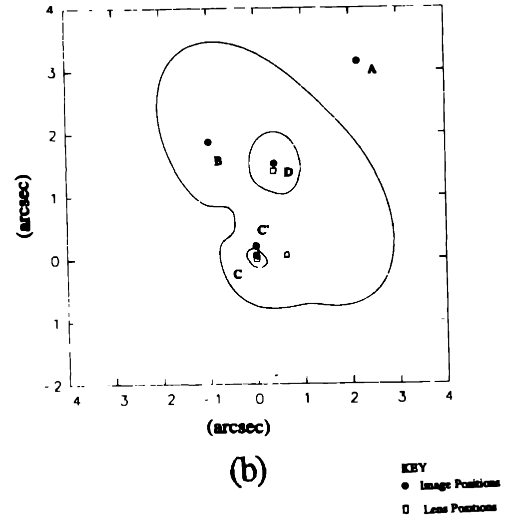
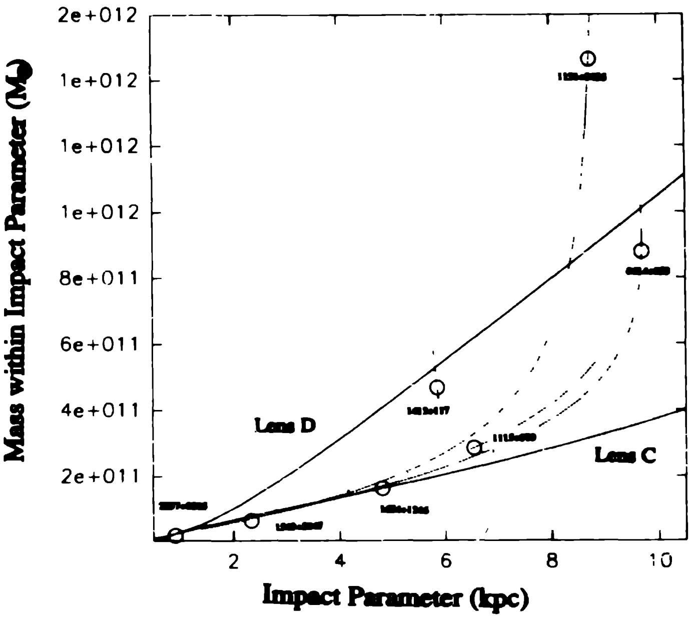


Figure 1(b). The corresponding image plane configuration. Open squares mark the lens positions. Images are shown by black dots, and the curves are the critical curves that are characteristic of this configuration.



(c)

Figure 1(c). Consistency check for the model lens structures (see text).

source should lie within the tangential caustic in source space for a typical elliptical potential, but this would produce more images than are observed. The lens at C draws one arm of the tangential caustic towards the lens centre so that the source lies outside of it, producing a match to the observations. This lens also helps to form the image at C′, which is faint compared to the principal images A and B. To do this, we need $z_{\rm C} \leq z_{\rm D}$.

What causes the image flux ratios to be different in different observations ? For gravitationally lensed compact images, the ratio of the flux in two images should be independent of wavelength. From table 1, we note that this is not the case for 2016+112. The behaviour of the ratio (C + C′)/A could be attributed to a wavelength dependent source structure that has an average magnification at C′ that varies with its size. There is also a contribution from the galaxy at C. This effect could operate for image C′, because it is close to a radial critical curve near C. [The structure of high redshift quasars observed up to now suggest that their morphologies tend to be rather complicated in the optical and infrared (Djorgovski 1988)]. The flux ratio A/B also varies with the waveband of observation. These images do not sample a rapidly changing lens potential as in the case of C′. If the source of the optical light lies ~0.06″ (about 400 pc) away from the dominant source of the radio emission, and towards the nearby radial caustic, we obtain an optical A/B ratio of 1.3. This causes a change in image separation of 0.15″ between the radio and optical observations, barely within the observational errors.

Are the lenses in the present model typical of galaxies ? We compare the lens structures obtained in our model against some galaxy-scale multiply imaged systems for which there is information on both the source and lens redshifts. Image systems are selected that have either quadruple or ring images. The mass contained within the impact parameter (here, the Einstein ring radius) is calculated for each system. Plotted in figure 1(c) against these values are the predicted values for lens distributions like C and D in the present model. The lens at C appears to be fairly typical of galaxies; the lens at D is rather more on the massive side, but resembles that in the case of the system H1413+117 (we recall that D is a giant elliptical). Thus galaxy plus halo structures could well be typical rather than exceptional.

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