The edge-on spiral gravitational lens B1600+434

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ABSTRACT

We present new observations of the gravitational lens (GL) system B1600+434, strongly suggesting that the lens is an edge-on spiral galaxy. These observations are used to constrain the mass model of the system, in particular the oblateness and velocity dispersion of the dark matter halo around the lensing galaxy. From an analytical model we find a lower limit on the halo oblateness $q_{\text{halo}} = (c/a)_{\rho} \gtrsim 0.4$; more detailed numerical models give a lower limit $q_{h} \gtrsim 0.5$. We determine an average halo velocity dispersion of $\sigma_{\text{halo}} = 190 \pm 15$ km/s over all non-singular isothermal elliptical (NIE) halo models. Constraining the models to larger and more massive disks, decreases this average by only 10 km/s. A lower limit of $\sigma_{\text{halo}} \gtrsim 150$ km/s is found, even for disk masses larger than the mass inside the Einstein radius. This lower limit indicates the need for a massive dark matter halo, contributing at least half of the mass inside the Einstein radius. Time delay calculations give $(54 \pm 3)/h_{50}$ days for the NIE halo model and $(70 \pm 4)/h_{50}$ days for the modified Hubble profile (MHP) halo model. Although the time delay for both NIE and MHP halo models is well constrained on our parameter grid, it strongly depends on the halo surface density profile. We furthermore find that the presence of a flat luminous mass distribution can severely alter the statistical properties of the lens.

Key words: Cosmology: dark matter - distance scale - gravitational lensing - galaxies: spiral - structure
1 INTRODUCTION

Over the last two decades, gravitational lensing has proved a very effective tool in constraining the shape of the mass distribution responsible for weak and strong lensing. Moreover, a time delay between two images can be used to determine the Hubble parameter, given an appropriate mass model (Refsdal 1964; 1966). In this paper we focus on the oblateness and velocity dispersion of the dark matter halo around the edge-on spiral galaxy lens in the GL system B1600+434 and calculate the expected time delays for this system for two different halo mass models.

Different techniques have been used to determine the oblateness \( q_{\text{halo}} = (c/a)_{\rho} \) of the dark matter halo around spiral galaxies. Most of these indicate an oblateness \( \gtrsim 0.4 \) (dissipationless N-body calculations, stellar dynamics in the solar neighborhood and polar ring galaxies (e.g. Rix 1995; Sackett 1995)). On the other hand, flaring of the gas layer and the HI velocity dispersion in NGC 4244 seem to indicate a more oblate dark matter halo with \( q_{\text{halo}} = 0.1-0.5 \) for that galaxy (Olling, 1996). This could support the idea that dark matter is mostly baryonic and perhaps consists of molecular hydrogen (Pfenniger, Combes & Martinet 1994; Pfenniger & Combes 1994). Obviously one would like to put stronger constraints on the oblateness of dark matter halos around spiral galaxies, less dependent of the chosen mass model, assumptions about the type of dark matter or its dynamical state. This opportunity is offered by the GL system B1600+434.

The lensing galaxy of B1600+434 is an edge-on spiral galaxy between two lensed QSO images and therefore presents the opportunity to determine the oblateness of the halo \( (c/a)_{\rho} \) by means of lensing. This method is different from and independent of methods used previously, in the sense that it is not dependent on the type of lensing matter (e.g. baryonic or non-baryonic) or its dynamical state.

In section 2 we describe new observations of B1600+434; in section 3 the basic lensing theory is summarized; in section 4 the mass models used to describe the lensing galaxy, its dark matter halo and the companion galaxy are presented; in section 5 we describe the parameter space of the fixed parameters in the mass models; and in section 6 we present our results and analyses. The main results are summarized in section 7.
2 OBSERVATIONS

The double QSO lens system B1600+434 was discovered by Jackson et al. (1995) in the Cosmic Lens All Sky Survey (CLASS; Myers et al. 1997). First we briefly summarize the observational status of this system and then present new radio and optical observations.

**Observational status** B1600+434 was discovered as a compact flat spectrum radio double with a separation of 1.39±0.01″. VLA 8.4 GHz observations show no structure due to extended emission (e.g. lobes) around the compact flat spectrum radio core and no sign of a central third image above the noise level is found (Jackson et al. 1995). On February 24 1996, B1600+434 was observed with the VLBA at 6 and 18 cm to search for possible substructure in the radio maps, which can further constrain a mass model for the lensing galaxy. The VLBA 18 cm maps of QSO images A and B do not show signs of substructure, but the 6 cm images show possible substructure 1–2 mas from the brightest component (Jackson, private communications). The redshift of the lensed source was measured to be 1.61 with the WHT (Jackson et al. 1995). Subsequently, more accurate redshifts of the source and the lens galaxy were determined with the Keck telescope (Fassnacht et al. 1998). The redshift of G1 was determined at 0.415 and the redshift of the source 1.59, consistent with the source redshift found previously. We will use the Keck redshifts, because of their superior S/N.

**HST observations** On November 18 1995, a 700 seconds WFPC2 HST I band and an 800 seconds V band exposure were obtained of B1600+434. The I band image clearly shows the two QSO images A and B, the lensing galaxy (G1) between the QSO images and the companion galaxy (G2) south-east of G1 (Fig. 1). The luminous component of G1 appears to be a flat edge-on system that exhibits a prominent dust lane. Both the dust lane and flat luminous mass distribution indicate that G1 is most likely a nearly edge-on spiral galaxy. The V band exposure shows both images A and B and galaxy G2, but not the lens galaxy G1.

We performed I and V band photometry on galaxies G1 and G2, on the small (∼ 3″) moderately inclined disk galaxy ∼ 10″ west of G1 (G3; see Jaunsen and Hjorth (1997) (JH97)) and on the QSO images A and B. We applied corrections for the gain of the different chips, the transfer efficiency and the long exposure time, amounting to a total correction in both V and I of approximately −0.08 magnitude. We also determined the magnitudes of two field stars S1 and S2 (stars 1 and 2 in JH97). The photometric results are listed in Table

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Comparing our HST photometry with the ground based photometry of JH97, we find that the magnitudes of all three galaxies and both stars do not differ by more than $\sim 0.1$ magnitude in both $V$ and $I$. However, over the same period (July to November 1995) the QSO images A and B have dimmed significantly. Image A by some 0.5-0.6 magnitudes in $V$ and 0.5 in $I$ and image B by some 0.2 magnitudes in both $V$ and $I$ bands. The decrease in brightness of image A is very significant and indicates strong optical variability over the order of months. The smaller decrease in brightness of image B can be explained by a time delay between the two images, which is also in the order of months (see section 6), but subtracting the emission of G1 could also have caused a systematic error in the brightness determination of image B. This effect will be stronger for less resolved ground based observations.

The companion galaxy G2 south-east of G1 appears to be a nearly face-on luminous barred spiral galaxy (Fig. 1). The bar-like structure can also be seen in the deconvolved NOT R band image (Fig. 2). From Fukugita, Shimasaku & Ichikawa (1995) we find that the HST F555W-F814W color of $1.40 \pm 0.15$ could either indicate an early type spiral galaxy at relative low redshift ($\sim 0.2$) or a somewhat later type spiral galaxy at higher redshift ($\sim 0.5$).

Judging from the bar-like structure G2 does not appear to an E/S0 galaxy, as suggested by JH97. As the photometric redshift of G2 is rather uncertain, we assume it to be the same as for G1 (0.415) as most reasonable first estimate. In section 6 we will describe the dependence of our results on this assumption. The small galaxy G3 is a moderately inclined (spiral) galaxy some 10′′ west of B1600+434. Because this galaxy is much smaller and $\sim 2$ magnitudes fainter than G2 ($\sim 6$ times less massive for the same M/L ratio and redshift), we do not incorporate this galaxy in the mass models (both the convergence and shear of G3 will be $\sim 10$ times smaller than that of G2 at images A and B).

**Nordic Optical Telescope observations** Exposures in B and R band (both 600 seconds) were taken July 30 1995 with the BroCam 1 camera (TEK1024 CCD) on the Nordic Optical Telescope (NOT). They show the lensing galaxy G1, the two QSO images and galaxy G2 (Fig. 2). Comparing the two QSO images in B and R, we clearly see the effect of extinction on image B, which almost passes through the dust lane of G1 (Fig. 1). To enhance the resolution, we deconvolved the R band image with the maximum entropy method ‘mem’ in the IRAF package STSDAS. The result clearly shows the extent of G1 ($\sim 7''$) and G2 ($\sim 5''$). There seems to be no clear evidence in the NOT and HST images to support the presence of a prominent massive bulge component in galaxy G1.
**MERLIN observations** On March 14 1995, a MERLIN 5 GHz observation was made of B1600+434 (Fig. 3). The map shows two compact (≈ 50 mas) radio components, with no visible sign of extended emission above the noise level. The flux densities of both components are given in Table 1. The flux ratio between components A and B is ≈ 1.2, comparable to the flux ratio from the VLA observations of Jackson et al. (1995). This consistency in flux ratio is either a coincidence (although VLA observation in August 1995 also indicate a flux ratio of ≈ 1.2 at 8.4 GHz, see Table 1) or the typical time scale of variability in the radio is much larger than the time delay, resulting only in slight variations in the radio flux ratio.

**Variability of the source** VLA 8.4 GHz observations of B1600+434 at two epochs indicate that the lensed source is variable by at least a factor of two over a period of one year (Table 1). Moreover, observations over a period of three months (April to July 1996) at 21 cm continuum with the WSRT (Fig. 4) indicate variability on time scales of the order of the expected time delay (section 6.3). It appears there is a steady decrease of flux density over this period, totaling ≈ 10% over three months.

This variability does not appear to strongly affect the flux ratio in the radio, which stayed between 1.2-1.3 at three epochs over a period of some two years. A ratio between the QSO images was found to be 1.38±0.05 in R (Jackson et al. 1995). Our new HST I band magnitudes give a ratio of 1.2±0.2. The observations of JH97 give a ratio of 1.6 in I (epoch 1). Although they could have underestimated the I magnitude of image B as a result of subtracting the lensing galaxy, it can also indicate a much stronger and perhaps more rapid variability in the optical. Furthermore, optical ratios will be effected by dust extinction and therefore give more or less upper limits, even if corrected for time delay. Overall our radio flux ratios appears to stay consistently around 1.2, whereas the optical ratios are slightly higher. We adopt a ratio $r_{AB} = 1.25 ± 0.10$.

### 3 LENSING THEORY

In describing basic lensing theory we will follow the definitions and notations as in Schneider, Ehlers & Falco (1992).

Given a length scale $\xi_0$ in the lens plane and the corresponding length scale $\eta_0 = \xi_0 D_s / D_d$ in the source plane we can define the dimensionless vectors
\[ x = \xi / \xi_0 \quad \text{and} \quad y = \eta / \eta_0. \] (1)

We can then define the dimensionless surface mass density
\[ \kappa(x) = \Sigma(\xi_0 x) / \Sigma_{cr}, \] (2)

where the critical surface mass density is given by
\[ \Sigma_{cr} = \frac{c^2 D_s}{4 \pi G D_d D_{ds}}. \] (3)

The lens equation
\[ \eta = \frac{D_s}{D_d} \xi - D_{ds} \hat{\alpha}(\xi) \] (4)

then becomes
\[ y = x - \alpha(x), \] (5)

with
\[ \alpha(x) = \frac{1}{\pi} \int_{R^2} d^2 x' \kappa(x') \frac{x - x'}{|x - x'|^2} = \frac{D_s D_{ds}}{\xi_0 D_s} \hat{\alpha}(\xi_0 x). \] (6)

We can then define the deflection potential
\[ \psi(x) = \frac{1}{\pi} \int_{R^2} d^2 x' \kappa(x') \ln |x - x'|, \] (7)

in order to get
\[ \alpha = \nabla \psi. \] (8)

The dimensionless lens equation then becomes
\[ y = \nabla \left( \frac{1}{2} x^2 - \psi(x) \right), \] (9)

which can also be written, using
\[ \phi(x, y) = \frac{1}{2} (x - y)^2 - \psi(x) \] (10)

as
\[ \nabla \phi(x, y) = 0. \] (11)

The image distortion from the source to the image plane can be described by the Jacobian matrix
\[ A(x) = \frac{\partial y}{\partial x} = \begin{bmatrix} 1 - \kappa - \gamma_1 & -\gamma_2 \\ -\gamma_2 & 1 - \kappa + \gamma_1 \end{bmatrix} \] (12)

with \( \kappa(x) \) being the local surface mass density (convergence) and the shear components
\[ \gamma_1 = \frac{1}{2} (\psi_{11} - \psi_{22}), \quad \gamma_2 = \psi_{12} = \psi_{21}. \] (13)
The magnification factor is then given by
\[ \mu(x) = \frac{1}{\text{det}A(x)} = \frac{1}{(1 - \kappa)^2 - \gamma^2} \]  
with
\[ \gamma^2 = \gamma_1^2 + \gamma_2^2. \]  

The time delay between to images at \( x^{(1)} \) and \( x^{(2)} \) is given by
\[ \Delta t = \frac{\xi_0}{c} \frac{D_s}{D_d D_{ds}} (1 + z_d) \left[ \phi \left( x^{(1)}, y \right) - \phi \left( x^{(2)}, y \right) \right]. \]  

Because \( \Delta t \propto \frac{1}{H_0} \) we can use the the above equation to determine the Hubble parameter \( H_0 \), given the observed time delay between two lensed images and an appropriate mass model for the lens (Refsdal 1964; 1966).

4 MASS MODEL

To model B1600+434, we construct a mass distribution consisting of 4 components: the luminous disk and bulge of G1, the dark matter halo around G1 and the combined luminous-dark matter distribution of galaxy G2. We will describe these components separately below. We use a Cartesian coordinate system and define our \( x_1 \)-axis to lie along the dust lane. The origin is defined on the point where \( x_1 \) and the line joining A and B intersect. The line joining images A and B makes an angle of \( 17^\circ \pm 2^\circ \) with the \( x_2 \) axis, consistent with what we find from our NOT images and the angle of \( 15^\circ \pm 3^\circ \) derived from JH97. We determine the image and galaxy positions with respect to this fixed coordinate system (Table 2). Fitting ellipses to the bright inner part of G1 (masking images A and B) in I band we find that the center of the brightness distribution of G1 is consistent with our defined origin (Fig. 1). This indicates that there is no significant angle between image A, the origin and image B. Lower surface brightness contours indicate a slight shift in the center of the ellipse center towards \( x_1 < 0 \), but smaller than the difference in lens center between us and Maller, Flores & Primack (1997), who used the results of JH97 to model B1600+434. The center of G1 that we use in this paper is also consistent with the position of the surface brightness of G1 in recent NICMOS H band observations by Jackson et al. (private communications). But much deeper optical or near infrared observations are still necessary to accurately pin down the center of G1.

In all calculations we will assume a smooth Friedmann-Robertson-Walker (FRW) uni-
verse with \( \Omega = 1, \Lambda = 0 \) and \( h_{50} = 1 \) (\( H_0 = 50 \cdot h_{50} \) km/s/Mpc), if not explicitly specified otherwise.

4.1 Disk and bulge and halo of G1

The surface brightness distribution of most disk galaxies can be described by an exponential profile (e.g. Mihalas & Binney 1981). Assuming a constant mass-to-light (M/L) ratio, the surface mass distribution of the disk of G1 becomes

\[
\Sigma_{G1,\text{disk}}(x_1, x_2) = \Sigma_{0,\text{disk}} e^{-\sqrt{(x_1^2+f_{\text{disk}}^2 x_2^2)/h_{\text{disk}}^2}},
\]

where \( h_{\text{disk}} \) is the radial exponential scale length and \( f_{\text{disk}} \) is the axis ratio of the disk surface brightness (mass) distribution projected on the sky. Although, when seen edge-on, this exponential surface mass distribution is not completely valid anymore, we assume that this relation stays valid in first order at large inclinations.

Many bulges can be well described by a de Vaucouleurs surface brightness profile, i.e. R\(^{1/4}\) law (e.g. Mihalas & Binney 1981). By also assuming that the M/L ratio is constant for the bulge, we find

\[
\Sigma_{G1,\text{bulge}}(x_1, x_2) = \Sigma_{0,\text{bulge}} e^{-7.67[(x_1^2+f_{\text{bulge}}^2 x_2^2)/r_e^2]^{1/4}}.
\]

From de Jong (1996) we find \( r_e \approx \frac{1}{3} \cdot h_{\text{disk}} \) and assume this relation to hold for the effective radius of the bulge of G1. We assume \( f_{\text{bulge}} = 0.6 \), as found for NGC891 (Bottema, van der Kruit & Valentijn 1991), which looks morphologically quite similar to G1. The optical extent of NGC891 (~30-35 kpc) is somewhat but not significantly smaller to that of G1 (~45 kpc, \( h_{50} = 1 \)). The disk mass of G1 is assumed 30 times more massive than the bulge mass (e.g. NGC891) in all our mass models. Although we have tried several models with free disk and bulge masses, they all give results in contradiction to our observations (section 6.1).

Because little is known about the actual surface mass distribution of the halo around disk galaxies, we model the halo around G1 with two different surface mass distributions: the non-singular isothermal ellipsoid model (NIE) and the modified Hubble profile (MHP). Following Kormann, Schneider & Bartelmann (1994) we find for the NIE models

\[
\Sigma_{G1,\text{halo}}(x_1, x_2) = \frac{\Sigma_{0,\text{halo}}}{\sqrt{1 + (f_{\text{halo}}^2 x_1^2 + x_2^2)/r_c^2}},
\]

where \( r_c \) is the halo core radius and \( f_{\text{halo}} \) the flattening. The velocity dispersion is defined as

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\[ \sigma_{\text{halo}}^2 = 2G\Sigma_{\text{halo}}^0 r_c \sqrt{f_{\text{halo}}}. \]  

(20)

For the MHP models we use

\[ \Sigma_{G1,\text{halo}}(x_1, x_2) = \frac{\Sigma_{G1,\text{halo}}^0}{1 + (f_{\text{halo}}^2 x_1^2 + x_2^2)/r_c^2}. \]  

(21)

We align the major axes of the disk, bulge and halo of G1 along the x1-axis and center them on the origin. Because G1 is close to edge-on, we assume that the axis ratio of the surface mass distribution of the halo is very close the its oblateness, hence \( f_{\text{halo}} = q_{\text{halo}} = (c/a)_{\rho,\text{halo}} \).

For inclinations \( \gtrsim 75^\circ \) and \( q_{\text{halo}} \gtrsim 0.5 \) the difference between \( f_{\text{halo}} \) and \( q_{\text{halo}} \) is \( < \sim 10\% \).

4.2 The galaxy G2

Because galaxy G2 appears to be a nearly face-on luminous disk galaxy, we use a non-singular isothermal sphere (NIS) as surface mass model, consistent with the assumption that disk galaxies have a flat rotation curve, as observed in many luminous nearby disk galaxies (e.g. Begeman 1987; Broeils 1992). The projected distance between G1 and G2 is \( \sim 30 \) kpc, a distance at which most of these galaxies still have flat rotation curves and the dark matter halo dominates the surface mass density (e.g. Begeman 1987; Broeils 1992). The oblateness \( q_{G2} = (c/a)_{\rho, G2} \) of the mass distribution of G2 doesn’t influence the radial profile of the surface mass distribution. We therefore assume that a NIS is a reasonable model to describe the surface mass distribution of G2 in first order

\[ \Sigma_{G2}(x_1, x_2) = \frac{\Sigma_{G2}^0}{\sqrt{1 + (x_1^2 + x_2^2)/r_{G2,c}^2}}, \]  

(22)

where \( r_{G2,c} \) is the core radius of the mass distribution of G2. The velocity dispersion is given by

\[ \sigma_{G2}^2 = 2G\Sigma_{G2}^0 r_{G2,c}. \]  

(23)

We assume a small core radius of 0.1 kpc. We center G2 on the position given in table 1 and assume the redshifts of G1 and G2 to be the same, as explained in section 2.

5 PARAMETER SPACE

Our knowledge of the galaxies G1 and G2 is rather limited by the low signal-to-noise and/or low resolution of the optical images. To asses the reliability of the results that we obtain on the halo flattening, halo velocity dispersion and time delay between the two lensed images, we examine a large grid of parameters that describe the mass distributions of G1 and G2.
We calculate a grid of \( \sim 5000 \) models using the NIE halo model, each with different core radius of the halo \( (r_c) \), velocity dispersion of galaxy G2 \( (\sigma_{G2}) \), radial exponential scale length of the disk of G1 \( (h_{\text{disk}}) \), disk mass of G1 \( (M_{\text{disk}}) \) and stellar disk flattening of G1 \( (f_{\text{disk}}) \) (see Table 3). We do the same for the MHP halo model. Keeping these parameters fixed, we vary the velocity dispersion \( \sigma_{\text{halo}} \) and flattening \( f_{\text{halo}} \) of the halo of G1 to achieve the minimum value of \( \chi^2 \) \( (\chi^2_{\text{min}}) \), where we define (Kayser 1990)

\[
\chi^2 \cdot N_{\text{dof}} = \frac{|y(x_A) - y(x_B)|^2}{\delta y^2} + \frac{|r_{AB} - \frac{J_B}{J_A}|^2}{\delta r_{AB}^2}.
\]  

Here \( y(x) \) is the lens equation, \( x_{A/B} \) are the positions of lensed images A and B, \( r_{AB} \) is the flux ratio, \( J_{A/B} \) are the Jacobians at \( x_{A/B} \) and \( N_{\text{dof}} = N_{\text{data}} - N_{\text{pars}} \) is the number of degrees of freedom. For the flux ratio we adopt an error \( \delta r_{AB} = 0.1 \), as explained in section 2. Furthermore \( \delta y \) is the position error of the source in the source plane. We examined different descriptions for \( \delta y \), because the circular error regions around the lensed images A and B do in fact not project back to circles on the lens plane, but project back onto ellipses. First we adopted a circular error region with \( \delta y = 0.02'' \), which roughly corresponds to an error of 0.05'' in the image plane for typical magnifications of a few. This error is comparable to the error of the image positions with respect to the lens center. A choise of the \( \delta y = 0.005'' \) does not change our results significantly. When projecting the error regions around the lens images back on the source plane, we find that they become two orthogonal ellipses. This increases the allowed region somewhat inside which the two lens images can be projected back on the source plane. However, redoing a sizeable subsample of our models indicates only a slight change in results, being on average only a shift of 10-20% of the rms value. This shift is therefore not significant.

Our choise of error region (0.05'' around both images) allows for a spread in image seperation, which is more than the observed 0.01'' (Jackson et al. 1995). So we also looked at those solutions with an image separation of 1.39 \( \pm 0.01'' \) and again find no significant change in our results compared with the other methods. We are therefore quite confident that our results are not strongly dependend on the choise of the allowed region \( (\delta y) \) in the source plane (e.g. the topology of the \( \chi^2 \)-space is quite robust as function of the error region). The results presented in this paper were obtained using the circular error region with \( \delta y = 0.05'' \).

* \( N_{\text{data}} \) is the number of constraints from the observations and \( N_{\text{pars}} \) is the number of free parameters in the mass model.
We minimize $\chi^2$ in the source plane to avoid having to search for the image positions, thereby significantly reducing the computational costs. Minimizing $\chi^2$ for the $\sim 10000$ models takes $\sim 5$ days CPU time on a SPARC 10 workstation. We minimise $\chi^2$ using a multi-dimensional Downhill Simplex method (Press et al 1992). Using $\sigma_{\text{halo}}$ and $f_{\text{halo}}$ at $\chi^2_{\text{min}}$, we calculate the time delay $\Delta t_{\text{AB}}$ between lensed images A and B (Eqn. 16) and the magnifications $\mu_A$ and $\mu_B$ (Eqn. 14).

In total we have 5 fixed parameters (Table 3) and 5 constraints (flux ratio, $x_1$ and $x_2$ positions of lensed images A and B, so $N_{\text{data}} = 5$). We solve for the position of the source ($x_s$ and $y_s$), the velocity dispersion of the halo $\sigma_h$ and the flattening of the halo $f_{\text{halo}}$ ($N_{\text{pars}} = 4$). To avoid under constraining the system we only solve for a total of 4 parameters ($N_{\text{dof}} = 1$).

### 5.1 Mass model parameters

Below we will describe our choice for the fixed parameter space. For each of the fixed parameters we take a broad range of values, in order not to exclude possible models beforehand. All parameters are listed in Table 3.

For the disk mass $M_{\text{disk}}$ we take values of $(1.0-20.0) \times 10^{10} M_\odot$, spanning the range where most ‘maximum disk’ masses of luminous disk galaxies lie (e.g. Broeils 1992). A ‘maximum disk’ mass maximizes the influence of the disk both on the dynamics and the lensing properties. From the deconvolved NOT R-band image (Fig. 2) we determine an axis ratio of the luminous disk of $\sim 0.3$. The HST I-band image however shows that most emission (partly bulge) lies clearly between the two QSO images, which are separated by 1.4″. This would imply an axis ratio $\lesssim 0.2$. We therefore choose to model the disk with axis ratios between 0.1 and 0.3, where an axis ratio of 0.1 is typical for an edge-on disk (spiral) galaxy. The scale length of the disk is hard to determine from either the NOT or the HST images. Also the dust lane makes such a determination hard. We therefore choose the large range of 1-16 kpc, knowing that the smaller values are probably too small (as is also true for the small disk masses). But these large parameter ranges make sure that we don’t underestimate the spread in the results that we obtain. We choose the halo core radius between 0.05 and 3.2 kpc, depending on the choice of mass model (NIE or MHP). The absence of the central third image seems to imply a high central surface density (small core radii; e.g. Narayan &

† The maximum disk mass is the maximum mass one can attribute to the luminous mass (stellar+gas) of a galaxy and still be in agreement with the observed HI rotation curve.
Bartelmann 1996), whereas rotation curve analyses seem to imply close-to ‘maximum disk’ galaxies and therefore large halo core radii (Rhee 1996; Broeils 1992). As a central massive black hole in lensing galaxies can significantly demagnify the central image, we won’t use the absence of this image as constraint on the core radius. For the velocity dispersion of G2 we take the very large range from 0 to 350 km/s. No velocity dispersion means that G2 has no influence on the lensing properties. A redshift of G2 different from G1 is approximately equivalent to decreasing its velocity dispersion. In section 6.1.1 we will estimate a velocity dispersion for G2 from its luminosity and use that to further constrain our results.

6 RESULTS AND ANALYSIS

Here we describe the results of the minimization of \( \chi^2 \) for the parameter space described in the previous section. We assume that the errors in the data have a Gaussian distribution. In which case 95% of the \( \chi^2 \) distribution of each individual model has \( \chi^2 < 4 \) for \( N_{\text{dof}} = 1 \). In the analysis we therefore only consider models with \( \chi^2_{\text{min}} < 4 \) and \( f_{\text{halo}} \leq 1 \) (oblate halo models), although in a sense the \( \chi^2 \) defined in the source plane is not exactly equivalent to that in the source plane. A smaller cut-off value (e.g. \( \chi^2_{\text{min}} < 1 \)) does not significantly effect the results. Each model is weighted equally in the determination of the average halo parameter values. Of the \( \sim 5000 \) NIE halo models, 736 have \( \chi^2_{\text{min}} < 4 \). Of the \( \sim 5000 \) MHP halo models 182 reach \( \chi^2_{\text{min}} < 4 \). This indicates that most combinations of the fixed parameters cannot lead to a satisfactory fit to the observational constraints. We will use all of the above models in the determination of the halo flattening, halo velocity dispersion and time delays between the two lensed images. We will also examine if there are correlations between the fixed parameters (Table 3) and the non-fixed parameters (\( \sigma_{\text{halo}} \) and \( f_{\text{halo}} \)).

6.1 Flattening of the halo

**Analytical models** First the flattening of the total lensing mass distribution (luminous+dark) is calculated, modeling G1 and its dark matter halo by a single Singular Isothermal Ellipsoidal (SIE) mass distribution. We assume that \( \theta_A = 1.14'' \), \( \theta_B = -0.25'' \) and \( \theta_G = -4.5'' \), with the lensed images and galaxy G2 lying on the \( x_2 \)-axis of the coordinate system. Using the exact positions of the lensed images and galaxy G2 gives essentially the same results. We find the relation (Kormann et al. 1994):
\[
\frac{|\theta_A - \theta_B|D_d}{\xi_0} = 2\sqrt{f} \frac{\sqrt{1 - f^2}}{f} \arcsinh \left(\frac{\sqrt{1 - f^2}}{f}\right),
\]  
(25)

with
\[
\xi_0 = 4\pi \left(\frac{\sigma}{c}\right)^2 \frac{D_d D_ds}{D_s},
\]  
(26)

independent of the presence of G2. In Eqns. 25 and 26, \(f\) is the axis ratio \((b/a)_\Sigma = (c/a)_\rho\) of the SIE mass distribution (\(f\) equals the oblateness for an edge-on mass distribution), \(\sigma\) is the velocity dispersion of the combined luminous+dark mass distribution, \(\xi_0\) is the Einstein radius, \(D_s\), \(D_d\) and \(D_ds\) are the angular diameter distances between respectively observer-source, observer-lens and lens-source. The magnification ratio is given by
\[
\frac{\mu_A}{\mu_B} = \frac{\left(1 - \frac{\xi_0}{D_d - |\theta_B|} - \left(\frac{\sigma_{G2}}{\sigma}\right)^2 \cdot \frac{1}{|\theta_B - \theta_{G2}|}\right)}{\left(1 - \frac{\xi_0}{D_d - |\theta_A|} - \left(\frac{\sigma_{G2}}{\sigma}\right)^2 \cdot \frac{1}{|\theta_A - \theta_{G2}|}\right)},
\]  
(27)

which can be reduced to
\[
\frac{\mu_A}{\mu_B} = \left[1 - 2(\kappa^B + \kappa_{G2}^B)\right] / \left[1 - 2(\kappa^A + \kappa_{G2}^A)\right],
\]  
(28)

where \(\kappa^{A/B}\) and \(\kappa_{G2}^{A/B}\) are the dimensionless surface densities (Eqn. 2) at the positions of the lensed images A and B. In Fig. 5 we plot the magnification ratio (flux ratio) given by Eqn. 28 as function of \(f\) and \(\sigma\). Using \(\mu_A/\mu_B = -1.25\), where the minus sign comes from the parity difference between the lensed images, we can solve \(f\) and \(\sigma\) from Eqns. 25-28. If a non-zero core radius is introduced in the mass distribution we find that for a constant flux ratio (\(|\mu_A/\mu_B|\)) the corresponding flattening \(f\) of the mass distribution increases. This implies that Eqn. 28 gives a lower limit on the flattening. Also the exclusion in Eqn. 28 of the flat luminous mass distribution implies that \(f\) is smaller than the flattening \(f_{\text{halo}}\) of the dark matter halo, because the combined luminous+dark matter is flatter then the dark matter (if \(f_{\text{disk}} < f_{\text{halo}}\)).

**Numerical models** One can compare the analytical results for the mass flattening with what is found from the more detailed numerical models where the disk, bulge and core radius of the halo are taken in to account. We examined the correlations between \(f_{\text{halo}}\) and the fixed parameters in Table 3 and only found a clear anticorrelation with \(\sigma_{G2}\). In Fig. 6 we plot the flattening \(f_{\text{halo}}\) of the NIE halo models against \(\sigma_{G2}\) for all models with \(\chi^2_{\text{min}} < 4\). If \(\sigma_{G2}\) increases \(f_{\text{halo}}\) decreases, which is qualitatively in agreement with the analysis given above (Fig. 5). The solutions of \(f_{\text{halo}}\) from these more detailed models are systematically slightly higher than the values found for \(f\) from Eqn. 28, especially for the smaller values of \(\sigma_{G2}\).
It is evident from Fig. 6 that $\sigma_{\text{G2}}$ is a very important parameter in the determination of limits on $f_{\text{halo}}$. In the next section constraints on $\sigma_{\text{G2}}$ will be derived, which are subsequently used to constrain $f_{\text{halo}}$, using both analytical and more detailed numerical models.

### 6.1.1 Velocity dispersion of G2 and limits on $f_{\text{halo}}$

To estimate the velocity dispersion $\sigma_{\text{G2}}$ we use the Tully-Fisher relation and the V-magnitude of galaxy G2. From our HST V-band observation we find a V-magnitude of 20.6 for G2, consistent with the results of JH97. From Coleman, Wu & Weedman (1980) we find a K correction of 0.6 and 1.2 for $(B-V)$ if G2 is a Sbc galaxy at $z_d = 0.415$; From JH97 $(B-V) \sim 1.4$. The luminosity is given by

$$L_B = 10^{0.4(M_B-5.48-(B-V)+DM+K)} L_\odot,$$

where $M_B=5.48$ is the total solar B magnitude and DM is the distance modulus. Using $z_d = 0.415$ we find $\text{DM}=42.2-5 \cdot \log(h_{50})$. The luminosity of G2 in B is then $L_B^{\text{G2}} \sim 4 \cdot 10^{10}/h_{50}^2$ $L_\odot$. Using this luminosity we find from Rhee (1996) that $\log v_f \approx 2.3 (h_{50} = 1)$, where $v_f$ is the rotation velocity of the HI gas in the flat part of the rotation curve. Using the relation $v_f \approx \sqrt{2}\sigma$ we find that the velocity dispersion of G2 must be $\sigma_{\text{G2}} \sim 140$ km/s, under the assumption that G2 can be described by a Singular Isothermal Sphere and that the local ($z = 0$) Tully-Fisher relation holds at a redshift of $z=0.4$. To find a strong upper limit on the velocity dispersion of G2 we go through the sample of luminous spiral galaxies of Broeils (1992) and Rhee (1996). No galaxies with $\log v_{\text{max}} > 2.54$ are found. This implies an upper limit on $v_{\text{max}}$ of 350 km/s, or an upper limit of about 250 km/s on the velocity dispersio of G2 ($\sigma \sim v_f/\sqrt{2}$). We find from Figure 6 that $\sigma_{\text{G2}} \sim 140$ km/s would imply an almost spherical halo with $f_{\text{halo}} \gtrsim 0.8$. The more stringent upper limit of $\sigma_{\text{G2}} \lesssim 250$ km/s gives a lower limit of $f_{\text{halo}} \gtrsim 0.5$. This compares well with the lower limit $f_{\text{halo}} \gtrsim 0.4$ for the same range of velocity dispersions of G2, which we find from equation 28 and Figure 5.

Moreover, Fig. 6 shows $f_{\text{halo}}$ plotted against $\sigma_{\text{G2}}$ for all MHP halo models with $\chi^2_{\text{min}} < 4$. For the range $\sigma_{\text{G2}} = 140 - 250$ km/s we find $f_{\text{halo}} \gtrsim 0.5$, identical to the limit on $f_{\text{halo}}$ from the NIE halo models.

Except for the strong anticorrelation between $\sigma_{\text{G2}}$ and $f_{\text{halo}}$, no other significant correlations are found. The spread in $f_{\text{halo}}$ for fixed values of $\sigma_{\text{G2}}$ appears therefore to result mainly from the spread in image positions and flux ratio.
So for both halo models (NIE and MHP) we find a lower limit $f_{\text{halo}} \gtrsim 0.5$ on the halo flattening, using the range of velocity dispersion of G2, $\sigma_{G2} = 140 - 250$ km/s. We also see that the lower limit on $f_{\text{halo}}$ is not strongly dependent on the chosen halo model. We recalculated a subsample of the models, using different starting values of $f_{\text{halo}}$ and $\sigma_{\text{halo}}$, finding the same solutions for both parameters for $\chi^2_{\text{min}}$. The agreement between the lower limits on $f_{\text{halo}}$ between the NIE and MHP halos are therefore not an artifact of the initial values of both parameters. Moreover one would expect to find lower values for $f_{\text{halo}}$ for the more centrally concentrated MHP models, compared with the NIE halo models. We find that the low $f_{\text{halo}}$ solutions for the MHP halo are mostly models with $r_c \geq 1.6$ kpc. These models are not very centrally concentrated and therefore allow for larger values of $f_{\text{halo}}$. The lower limits therefore appear genuine and not artificial.

From the analytical models (Figure 5) we find that the flux ratio $r_{AB}$ strongly constraints the flattening of the SIE mass distribution. An error of $\pm 0.05''$ in the distance of images A and B to the lens center of G1 gives an error of 0.1 in the flattening. Using the same range of $\sigma_{G2} = 140 - 250$ km/s, we find a lower limit on the combined mass distribution (halo+disk+bulge) of $0.40 \pm 0.1$. Because the disk is much flatter than the halo and on first sight much more massive than the bulge, the same lower limit applies to the halo. Moreover a non-zero core radius will increase the value of $f_{\text{halo}}$.

Moreover, we have tried modeling B1600+434, using only the disk and bulge components. If we constrain the bulge mass, we find that the axis ratio of the disk typically will increase to $f_{\text{disk}} \gtrsim 0.5$, larger than the observed limit of 0.3. On the other hand, if the disk flattening is constraint to $\leq 0.3$, we find solutions that required extremely large bulge masses ($M_{\text{bulge}} > M_{\text{disk}}$). This again supports the need for a mass component rounder than the disk, but much more massive than the bulge.

### 6.1.2 Critical curves and caustics

In Fig. 7 the critical and caustic curves for two distinct NIE halo mass models are shown. Both models give good fits to the observed image positions and flux ratio, but the critical and caustic structure is quite different.

Fig. 7a and 7b both show a mass model with an almost spherical halo and velocity dispersion near 200 km/s. The difference between both models is the mass and flattening (axis ratio) of the disk. Also the velocity dispersion of G2 is different between both models. It
is already evident from these two models that the presence of a flat stellar mass distribution can significantly alter the critical and caustic structure of the lens and still be in agreement with the observed image positions and flux ratio. The model shown in Fig. 7a has a larger 5-image cross section and one expects therefore a different ratio of 5 to 3-image systems between these models. A precise model of the stellar mass distribution is therefore needed to understand exactly the statistical properties of gravitational lenses with highly flattened luminous mass distributions. This is particularly evident in the case of B1600+434. A more detailed analysis of the statistics of spiral galaxy lenses can be found in Koopmans & Nair (1997).

All our models place the source position close to the radial caustic, whereas Maller et al. (1997) find a source position close to the tangential caustic. This is the result of a difference in adopted lens center. The difference between our and their lens center is $\sim 0.2''$, whereas our HST observations allow only a $\sim 0.05''$ difference. If we move our lens center to the position found by Maller et al. (1997), we find that the source position moves from the radial to the tangential caustic. Our observations allow a very small shift in the lens center, but much smaller than 0.2''. This shift would move the source position slightly away from the radial caustic.

### 6.1.3 The importance of the redshift of G2

From Kochanek & Apostolakis (1988) we find that two lenses interact significantly if the transverse separation between the two lenses is $\lesssim 4$ times the radius of the outer critical curve. From Fig. 7 we find that the radius of the outer critical curve in the direction of G2 is $\sim 0.7''$ (approximately the Einstein radius or half the image separation). We see that $4 \times 0.7'' = 2.8'' < 4.5''$, where the separation between G1 and G2 is $\sim 4.5''$. Although the critical curves of G1 will be somewhat distorted (Figure 7), galaxy G2 can in first order be approximated by a perturbing external shear. The strength of this shear is a function of both the redshift and velocity dispersion of G2. According to Kochanek & Apostolakis (1988) both lenses will work together most efficiently, if they are at the same intermediate redshift. Changing the redshift of G2, will therefore decrease the strength of this perturbing shear, which in first order is equivalent to decreasing the velocity dispersion of G2. This effect only becomes significant when $z_{\text{G2}}$ is outside the range of $z_{\text{G1}} \pm 0.3 = 0.1 - 0.7$. Furthermore, a much higher redshift for G2 can change the geometrical part of the timedelay surface,
changing the expected time delay. However, the colors of G2 seem to indicate that a redshift smaller than 0.4 is more likely than a redshift larger than 0.4. The B-V and V-I colors from JH97 and our F555W-F814W colors indicate that a redshift of 0.8 for G2 cannot be accomodated by either E/S0 or spiral galaxies. A much larger redshift than 0.4 is therefore unlikely for G2. The effect of G2 on the timedelay will therefore in first order be included in our range of velocity dispersion for G2 and as we will see the effect of G2 will be marginal.

### 6.2 Velocity dispersion of the halo

In this section we will describe our results for the velocity dispersion of the NIE halo. We only give the results of $\sigma_{\text{halo}}$ for the NIE halo models, because it can directly be related to rotation curve observations of spiral galaxies.

**Velocity dispersions and mass** From Eqns. 25 and 26 we find that $\sigma_{\text{halo}} \approx 200 \text{ km/s}$, nearly independent of the flattening of the halo ($(\theta_A - \theta_B)D_d/\zeta_0 \approx 2$ for $f \gtrsim 0.1$). This velocity dispersion implies a total mass inside the Einstein radius $M(\xi < \zeta_0) \approx 1.3 \cdot 10^{11} M_{\odot}$ ($h_{50} = 1$). In Fig. 8 we plot the histogram of $\sigma_{\text{halo}}$ for the NIE halo models with $\chi^2_{\text{min}} < 4$. It appears that $\sigma_{\text{halo}}$ is restricted to a small range of values. Simply taking the average for all models with $\chi^2_{\text{min}} < 4$ we find $\sigma_{\text{halo}} = 190 \pm 15 \text{ km/s}$, consistent with what we found analytically. This velocity dispersion gives a rotation velocity outside the optical disk of $v_f \approx 270 \text{ km/s}$, comparable to rotation velocities found for large luminous spiral galaxies (e.g. Broeils 1992). Restricting to the larger and more massive models with $h_{\text{disk}} \geq 8 \text{ kpc}$ and $M_{\text{disk}} \geq 5 \cdot 10^{10} M_{\odot}$, we find only a slight decrease in the halo velocity dispersion, $\sigma_{\text{halo}} = 180 \pm 15 \text{ km/s}$. Both distributions have a wing towards to lower velocity dispersions (Figure 8).

Using the WFPC2 F814W magnitude of 20.2 and the V-F814W=$2.0$ magnitude for a Sab galaxy at $z \sim 0.5$ (Fukugita et al. 1995), we expect a lower limit (due to dust obscuration) on the V magnitude of 22.2, close to the 22.0 found by JH97. This results in a luminosity of $L_B^{G1} \sim 10^{10} L_{\odot}$. From Rhee (1996) we expect that an Sab galaxy at this redshift should be $\sim 2.5$ magnitudes brighter in B. This difference again indicates the presence of a large amount of obscuring dust. Calculating a sensible mass-to-light ratio is therefore difficult in the inner parts of G1. Moreover the presence of image B in the bulge of G1 makes this even harder. Because of the expected few magnitudes of extinction, the M/L ratio of 51 in
B (JH97) could be $\sim 5 - 10$ times smaller. The ratio would then be in the range of spiral galaxies.

**Correlations of $\sigma_{\text{halo}}$ with disk mass** We find an anti-correlations between the $\sigma_{\text{halo}}$ and $M_{\text{disk}}$ (Fig. 9). The separation between the two lensed images is a strong function of the mass inside the Einstein radius. This means that an increase in $M_{\text{disk}}$ increases the mass inside the Einstein radius (between the lensed images). This increase in mass must be compensated by the other mass component, the dark halo, hence $\sigma_{\text{halo}}$ decreases. For the massive disk models ($M_{\text{disk}} \gtrsim 10^{11} M_\odot$) we find that only models with large exponential scale lengths $\gtrsim 4 \text{ kpc}$, give solutions with $\chi^2_{\text{min}} < 4$ and that $\sigma_{\text{halo}}$ does not drop below $\sim 150 \text{ km/s}$ (for $\sigma_{G2} \lesssim 250 \text{ km/s}$). We conclude that even very high disk masses (masses larger than that needed for the image splitting) do not significantly reduce the velocity dispersion of the halo. Indeed a massive halo is in needed to fit the observations. Also a small anti-correlation is found between $\sigma_{\text{halo}}$ and $\sigma_{G2}$, which could be explained by the model trying the match the flux ratio when changing $\sigma_{G2}$.

### 6.3 Time delay

For the SIE mass distribution and under the same assumptions as in section 6.1.1 we find for the time delay between the lensed images (Kormann et al. 1994):

$$\Delta t_{AB} = \frac{\xi_0}{c} \frac{D_{\text{ds}}}{D_{\text{ds}}} (1 + z_d) \frac{\sqrt{f}}{\sqrt{1 - f^2}} \cdot \text{arccosh} \left( \frac{1}{f} \right) (|\theta_A| - |\theta_B|).$$

Eqn. 30 is equivalent to the time delay without the presence of G2 in the mass model. This indicates that one does not expect a very large influence of G2 on the time delay between the lensed images. Using Eqn. 25 we can reduce Eqn. 30 to

$$\Delta t_{AB} = \frac{1}{2c} \left( \frac{D_d D_s}{D_{\text{ds}}} \right) (1 + z_d) |\theta_A - \theta_B| (|\theta_A| - |\theta_B|)$$

For $z_d = 0.415$, $z_s = 1.59$, $\theta_A = 1.14''$, $\theta_B = -0.25''$ and an error in $\theta_{AB} \sim 0.05''$ we find a time delay $\Delta t_{AB} = (57 \pm 7)/h_{50}$ days. We will now compare this predicted time delay with the time delays found from our numerical models.

In Fig. 10 we plot the histogram of the time delay for all numerical models with $\chi^2_{\text{min}} < 4$. We see in this figure that the time delay depends only weakly on variations in the input model parameters. Taking the average of all time delays with $\chi^2_{\text{min}} < 4$ we find $\Delta t_{AB}^{\text{NIE}} =$

---

$\dagger$ e.g Most of the disk mass is outside the Einstein radius.
(54 ± 3)/h_{50} days. Using only the larger and more massive models with $h_{\text{disk}} \geq 8$ kpc and $M_{\text{disk}} \geq 5 \cdot 10^{10} M_{\odot}$, we find $\Delta t_{\text{NIE}}^{\text{AB}} = (53 \pm 3)/h_{50}$ days. This is in excellent agreement with the time delay we found from our simple analysis, indicating the stability of the time delay against changes in the fixed NIE model parameters.

In Fig. 10 we also plotted the histogram of the time delay for all MHP models with $\chi^2_{\text{min}} < 4$. Taking the average of these time delays, we find $\Delta t_{\text{MHP}}^{\text{AB}} = (70 \pm 4)/h_{50}$ days. For the larger more massive models we find $\Delta t_{\text{MHP}}^{\text{AB}} = (68 \pm 2)/h_{50}$ days. Also for the MHP halo models a small spread in the time delay is found. It is therefore clear, as in the case of the NIE halo model, that changes in the fixed model parameters do not severely influence the time delay between the lensed images. We have not calculated the time delay for the MHP mass models analytically.

The difference in time delays between the MHP and NIE halo models are $\sim 30\%$, because the more centrally concentrated MHP mass distribution gives rise to a much larger potential time delay between images A and B. Although the flat rotation curves of spiral galaxies seem to favor a NIE mass distribution, we do not know the distribution of mass in the $z$-direction very well. More constraints on the mass distribution are therefore needed (e.g VLBI structure in the images A and B).

### 6.4 Magnification of images A and B

We have calculated the magnification of the lensed images for every model with $\chi^2_{\text{min}} < 4$. The averages of the magnifications and flux ratios for the NIE and MHP halo models are listed in Table 3. We see that the average magnifications for both halo models are not very large, but typical for a two image system. One also notes that the magnification from the MHP halo models is smaller than the magnification from the NIE halo models. The difference between the magnifications is about 33\%, which results in a different calculated absolute magnitude for the lensed source for the two (NIE and MHP) halo models.

### 7 CONCLUSIONS

New HST and NOT observations of the GL system B1600+434 strongly suggest that the lensing galaxy in this system is an edge-on spiral galaxy. Because the system is nearly edge-on, we can use the lensing properties of this system to constrain the velocity dispersion and oblateness (flattening) of the dark matter halo around the lensing spiral galaxy. This system
is unique in the sense that for the first time gravitational lensing has been used to constrain the dark matter distribution around an individual spiral galaxy. Moreover, the lensed QSO is highly variable both in the radio and the optical and can therefore be used to determine the time delay between the two lensed images. This time delay gives us either $H_0$, once the mass model has been well constrained, or an extra constraint on the mass model, once $H_0$ has been constrained from other GL systems (e.g. B0218+357, B1608+656, etc).

7.1 Flattening of the halo

From detailed numerical modeling we find a lower limit of $f_{\text{halo}} \gtrsim 0.50$ on the axis ratio of both the NIE and MHP halo mass distribution around the edge-on spiral galaxy lens in B1600+434.

When we use a simplified analytical SIE mass model we do not find a surface mass distribution significantly flatter than $\sim 0.4$. Using a core radius $r_c > 0$ increases this limit. This lower limit is significantly larger than the typical flattening ($\sim 0.1$) of the luminous stellar component of spiral galaxies and also larger than the upper limit on the flattening of G1 ($\lesssim 0.3$) from the HST and NOT observations. We conclude that the halo dark matter around G1 is not as flat as the luminous stellar component (or gas). This implies that the suggestion by Pfenniger at al. (1994), that dark matter could be cold molecular hydrogen associated with HI gas, is inconsistent with our results for G1. In that case one would expect to find a halo flattening in the same order or smaller than the luminous stellar component ($f_{\text{halo}} \leq f_{\text{disk}}$), which we clearly do not find.

7.2 Velocity dispersion and mass of the halo

The average velocity dispersion over all models of the NIE halo is found to be $190 \pm 15$ km/s, which gives a rotation velocity outside the optical disk of $\sim 270$ km/s ($f_{\text{halo}} \sim 1$), consistent with luminous spiral galaxies (e.g. Broeils 1992). For large disk masses ($10 - 20 \cdot 10^{10} \, M_\odot$) the velocity dispersion of the halo decreases, but never drops below $\sim 150$ km/s, even for disk masses larger than the mass needed for the image splitting. This indicates that a massive halo is needed around the much flatter luminous stellar component to fit the observed image positions and flux ratio.

The mass inside the Einstein radius is $\sim 1.3 \cdot 10^{11} M_\odot$ of which at least half (if $\sigma_{\text{halo}} \gtrsim 150$ km/s) can be attributed to the halo. Using the Tully-Fisher relation and the observed $10^{10} L_\odot$...
in the B band, we suspect some 2.5 magnitudes of extinction in the B band. If this is the case, the mass-to-light ratio of 51 in B (JH97) would be reduced to $\sim 5$, consistent with spiral galaxy mass-to-light ratios.

### 7.3 Time delay

The time delays found for the different halo models are quite different and do not significantly depend on the presence of G2. The NIE halo model gives in a time delay of $\Delta t_{A/B}^{\text{NIE}} = (54 \pm 3)/h_{50}$ days, whereas the MHP halo model gives $\Delta t_{A/B}^{\text{MPH}} = (70 \pm 4)/h_{50}$ days. These delays decrease by only a few percent if only models with $h_{\text{disk}} \geq 8 \text{kpc}$ and $M_{\text{disk}} \geq 5 \cdot 10^{10} M_\odot$ are used. It is clear that more observations are necessary to constrain the mass model and discriminate between different halo mass models. Because flat rotation curves of spiral galaxies seem to point at a NIE halo, the time delay from the NIE halo model is probably closest to the actual time delay. The time delay from the MHP can still be used to put an upper limit on $H_0$.

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Captions:

**Fig.1**: HST I band image. North is up, east is left.

**Fig.2**: 
Upper: Nordic Optical Telescope (NOT) B band image, 
**middle**: NOT R band image, 
lower: deconvolved NOT R band image. 1" corresponds to a physical size of 6.5 kpc at redshift $z_l = 0.415$ and $h_{50} = 1$.

**Fig.3**: MERLIN 5 GHZ observation of B1600+434 (March 14, 1995).

**Fig.4**: Total flux density of the two QSO images at 21 cm radio continuum measured with the WSRT as a function of time from April 8, 1996. The error bars indicate the flux error in fitting the model to the visibilities.

**Fig.5**: The flux ratio $|\mu_A/\mu_B|$ plotted as function of $f$ for $\theta_B = -0.20''$ (dot), $-0.25''$ (dash), $-0.30''$ (long dash) and for $(\sigma_{G2}/\sigma) = 0.5$, 1.0, 1.5, 2.0, using a simple SIE surface mass model to describe G1 and SIS mass model for galaxy G2. The horizontal solid line gives the flux ratio of 1.25, the dotted lines border the region 1.15-1.35.

**Fig.6**: The flattening parameter $f_{\text{halo}}$ plotted against $\sigma_{G2}$ for the NIE (square) and MHP halo models (triangle) with $\chi^2_{\text{min}} < 4$. The velocity dispersion $\sigma_{G2}$ has been shifted by -3 km/s and +3 km/s for respectively the NIE and MHP halo models.

**Fig.7**: The critical lines (dashed) and caustics (solid) for two distinct NIE halo mass models of B1600+434 with an NIE halo. The small plusses give the model positions of the lensed images. The circles give the positions of the lensed images listed in Table 1. The larger cross indicates the calculated position of the source in the source plane. The large shift in the position of the caustics is the result of the presence of G2. In the upper figure (a) we see a model with $r_c = 0.40$ kpc, $f_{\text{halo}} = 0.89$, $\sigma_{\text{halo}} = 199$ km/s, $h_{\text{disk}} = 8$ kpc, $f_{\text{disk}} = 0.1$, $M_{\text{disk}} = 5.0 \times 10^{10} M_{\odot}$ and $\sigma_{G2} = 150$ km/s. In the lower figure (b) we see a model with $r_c = 0.40$ kpc, $f_{\text{halo}} = 0.95$, $\sigma_{\text{halo}} = 193$ km/s, $h_{\text{disk}} = 8$ kpc, $f_{\text{disk}} = 0.3$, $M_{\text{disk}} = 1.0 \times 10^{11} M_{\odot}$. 
and $\sigma_{G2} = 200$ km/s.

**Fig.8:** Histogram (solid) of the velocity dispersion of the NIE halo for $\chi^2_{\text{min}} < 4$. The dashed histogram are those models with $M_{\text{disk}} \geq 5 \cdot 10^{10} \, M_\odot$ and $h_{\text{disk}} \geq 8$ kpc.

**Fig.9:** Correlation between $\sigma_{\text{halo}}$ and $M_{\text{disk}}$ for the NIE halo model.

**Fig.10:** Histogram of the NIE (upper) and MHP (lower) model time delays for $\chi^2_{\text{min}} < 4$. The dashed histograms are those models with $M_{\text{disk}} \geq 5 \cdot 10^{10} M_\odot$ and $h_{\text{disk}} \geq 8$ kpc.
Table 1. Column 1-2: HST V and I band magnitudes of the GL system B1600+434 (November 18, 1995). The stars were saturated in I. G1 was not seen in V. Column 3: MERLIN 5 GHz flux density (mJy) (March 14, 1995). Column 4-5: VLA 8.4 GHz flux densities (mJy) in March 1994 (1) and August 1995 (2).

<table>
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<tr>
<th></th>
<th>V (magn.)</th>
<th>I (magn.)</th>
<th>$S_5$</th>
<th>$S_{8.4}^1$</th>
<th>$S_{8.4}^2$</th>
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<td>22.5 ± 0.1</td>
<td>21.4 ± 0.1</td>
<td>45.2</td>
<td>58.1</td>
<td>28.5</td>
</tr>
<tr>
<td>B</td>
<td>23.1 ± 0.1</td>
<td>21.6 ± 0.1</td>
<td>37.3</td>
<td>48.1</td>
<td>23.8</td>
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<tr>
<td>G1</td>
<td>—</td>
<td>—</td>
<td>20.2  ± 0.1</td>
<td></td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>20.6 ± 0.1</td>
<td>19.2 ± 0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>G3</td>
<td>22.5 ± 0.1</td>
<td>21.0 ± 0.1</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

S1 | 17.73 | — |
S2 | 17.86 | — |

Table 2. Positions and flux ratio of images and positions of galaxies G1 and G2, w.r.t. the defined origin of the coordinate system.

<table>
<thead>
<tr>
<th></th>
<th>$x_1$ (&quot;)</th>
<th>$x_2$ (&quot;)</th>
<th>Flux</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>-0.33±0.01</td>
<td>1.09±0.01</td>
<td>1.25±0.10</td>
</tr>
<tr>
<td>B</td>
<td>0.07±0.01</td>
<td>-0.24±0.01</td>
<td>1.00</td>
</tr>
<tr>
<td>G1</td>
<td>0.00±0.05</td>
<td>0.00±0.05</td>
<td></td>
</tr>
<tr>
<td>G2</td>
<td>-0.80±0.10</td>
<td>-4.40±0.10</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Parameters used for the NIE and MHP halo models. The parameters within parenthesis are only used for the NIE models. The parameters within brackets are only used for the MHP models.

<table>
<thead>
<tr>
<th></th>
<th>NIE</th>
<th>MHP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\mu_A$</td>
<td>2.69±0.26</td>
</tr>
<tr>
<td>$\mu_B$</td>
<td>-2.14±0.22</td>
<td>-1.64±0.11</td>
</tr>
<tr>
<td>$\mu_A/\mu_B$</td>
<td>-1.25±0.03</td>
<td>-1.24±0.03</td>
</tr>
</tbody>
</table>

Table 4. Average magnifications and flux ratios of the source for images A and B.