THE ASTROPHYSICAL JOURNAL, 383:66–71, 1991 December 10

THIN AND GIANT LUMINOUS ARCS: A STRONG TEST OF THE LENSING CLUSTER MASS DISTRIBUTION

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Received 1991 April 24; accepted 1991 June 11

ABSTRACT

New expressions are given for the gravitational magnification and the ratio between source and image sizes, which apply to the giant thin and luminous arcs found in distant cluster cores, and for any number of lenses in the cluster. Source properties are strongly dependent on the a priori choice of the lensing mass density profile. The new formulae provide the first attempt to disentangle the properties of the lensing clusters from the arc source properties. Available observations—spectroscopy, imagery and photometry—are used to constrain the nature of the sources, which are probably spiral galaxies, and hence, to derive new and independent conditions on the mass density profile of the dark matter inside the lensing clusters. Most of the lensing clusters should be much more compact than inferred from their X-ray density profiles and even more compact than inferred from their visible luminosity profile, except if there was an enormous evolution of the entire luminosity function of galaxies from $z \leq 0.4$ to $z \approx 0.8$. Indeed lensing clusters should have mass density profiles more compact than isothermal spheres with small core radii ($r_c \leq 100$ kpc for $H_0 = 50$). It is also argued that the sources of the small and faint arclets found in deep images of distant clusters, could be dwarf galaxies at moderate redshift ($z \leq 1$). The new test presented here to derive lensing mass distribution is finally compared with the method using arclets.

Subject headings: dark matter — galaxies: clustering — gravitational lenses

1. INTRODUCTION

The giant luminous arcs found (Soucail et al. 1987a; Lynds & Pétrosian 1986) in cores of rich distant clusters have raised much hope for the determination of the lensing matter and the study of sources that would be beyond the reach of the largest telescopes if they were not lensed. Nowadays, less than 10 very elongated images—axis ratio less than one-tenth—have been discovered in distant cluster cores. Most of them are relatively luminous (surface brightness $\approx$ 24–24 mag arcsec^{-2} in blue) are thin (unresolved and thinner than 0"5 up to thickness of 1"3). Their blue colors contrast with the red cluster galaxies that inhabit the core. Strong lensing events may favor blue sources because counts are slightly steeper in blue than in red (Hammer 1990). Spectroscopic measurements of the brightest arcs (B = 21–22.5) are secure at least for four of them, although sometimes based on a single emission line, as for the arc in A963 (Ellis, Allington-Smith, & Smail 1991). These lines have no identification at the cluster redshift and are probably [O II]λ3727 supported by the detection of a 4000 Å break for the arcs found in A370 (Soucail et al. 1988), Cl0500−24 (Giraud 1990, private communication) and A2390 (Pello et al. 1991). Then the arc spectra are very similar to the ones of galaxies found in deep redshift surveys (Broadhurst, Ellis, & Shanks 1988, hereafter BES; Colless et al. 1990, hereafter CETH; Lilly, Cowie, & Gardner 1991, hereafter LCG) except that the arc sources have redshift ranging from 0.72 to 0.92. Note the case of the arc in Cl2244−02, which was claimed (Soucail et al. 1989) to lie at $z = 2.3$ on the basis of a line which uncomfortably lies at the blue and noisy edge of the spectrum and was identified as Lyα.

The giant arcs are well extended over 10" or more and they apparently draw the lensing geometry. Several of them have been successfully modeled on the assumption that the lensing mass was the sum of the masses concentrated on the cluster center and on each cluster galaxy or group in the cluster. Deep imagery and galaxy counts have helped to find the cluster centers, and generally, the number of (lensing) parameters is comparable to the number of (observational) constraints (Hammer et al. 1988; Hammer & Rigaut 1989). This should be compared to the multiple QSO configurations which bring a very inaccurate mass determination mainly due to the lack of constraints provided by their unresolved images. However models seem insensitive to the adopted density profile since multipoint mass models (Hammer 1987) for the lenses fits the arcs as well as multiple $r^{1/4}$ surface density profiles (Hammer & Rigaut 1989) or multiple isothermal profiles (Grossman & Narayan 1989). Indeed the lensing critical radius—at first approximation the arc radius—depends only on the amount of mass projected inside the arc.

The first goal of this paper is to point out how all the source properties derived from the lensing equations strongly depend on the a priori choice of the lensing mass density profile. This will be established in the case of giant luminous arcs by setting new formula for gravitational magnification and for the ratio of the arc thickness over the source size, both quantities depending only on the lens surface density at the arc location. Similarities of the arc source properties with sources which are dominant in deep spectroscopic surveys provide a new and independent test to constrain the lensing mass density profile. This leads to a deconvolution of the source and lens properties for giant luminous arcs and also for the mini-arcs found in distant cluster cores (Fort et al. 1988; Tyson, Waldes, & Wenk 1990).

2. GENERAL THEORY OF ARC THICKNESS AND ARC SOURCE MAGNIFICATION

We have previously pointed out (Hammer & Rigaut 1989) that the arc thickness was intimately related to the intrinsic source size. For a multiple point mass model, we found that, for large magnifications, the arc thickness was exactly one-half of the corresponding source size. For a single elliptical smooth lens, the magnification, *Amp*, could be expressed as (Bourassa & Kantowski 1975): $Amp^{-1} = (1 - K)^2 - \Gamma^2$, where K (matter or Ricci term) corresponds to the beam expansion due to the matter lying inside the beam while Γ (shear or Weyl term) corresponds to the beam distortion due to the matter lying outside the beam. Hence for such a single lens, it is straightforward from the Bourassa & Kantowski (1975) formalism that

$$(\text{arc thickness/source size}) = 1/[2(1 - K)] + O(1/Amp) , \quad (1)$$

where $K = (4\pi G/c^2 D_d D_{ds}/D_s \sigma)$ and the surface density σ took its value at the arc location. Angular diameter distances were used here, D_d, D_{ds} and D_s being the deflector, the source-deflector and the source distances, respectively.

Let us now consider two spherical lenses with surface density $\sigma_1(r)$ and $\sigma_2(r)$ and located at $\alpha_1(x_1, y_1)$ and $\alpha_2(x_2, y_2)$ in a same lens plane—defined by D_d. The lensing equations—relations between image location $\theta(x, y)$ and virtual source location $\phi(x_s, y_s)$—are

$$\theta - \phi = 8\pi G/c^2 D_{ds}/(D_d D_s) \sum_{i=1}^{2} \left\{(\theta - \alpha_i)/|\theta - \alpha_i|^2 \times \int_0^{D_d|\theta - \alpha_i|} r\sigma_i(r)\, dr\right\} . \quad (2)$$

The magnification factor is $Amp = (\det J)^{-1}$, where J is the Jacobian of the lensing equations, and its two eigenvalues λ will bring us the relationship between the image thickness and the source size: $\det (J - \lambda I) = 1/Amp - S\lambda + \lambda^2 = 0$, where S is the trace of the matrix and is unaffected by a change of the referential. Indeed $S = \partial x_s/\partial x + \partial y_s/\partial y$, and

$$1 - \partial x_s/\partial x$$
$$= 8\pi G/c^2 D_{ds}/(D_d D_s)\left\{\sum_{i=1}^{2} [D_d^2(x - x_i)^2/|\theta - \alpha_i|^2 \sigma_i(D_d|\theta - \alpha_i|)] + \sum_{i=1}^{2} [1/|\theta - \alpha_i|^2 - 2(x - x_i)^2/|\theta - \alpha_i|^4]\left[\int_0^{D_d|\theta - \alpha_i|} r\sigma_i(r) dr\right]\right\} ,$$

while $\partial y_s/\partial y$ is given by the same relation, just by replacing x by y. It comes

$$S = 2 - 8\pi G/c^2 D_d D_{ds}/D_s \sigma_1 - 8\pi G/c^2 D_d D_{ds}/D_s \sigma_2 = 2(1 - K_1 - K_2) . \quad (3)$$

This could be easily generalized to a set of $n \geq 2$ lenses in a given lens plane, and then the arc magnification along the arc width is

$$k_{//} = [\![1 - \Sigma(K) + \{[1 - \Sigma(K)]^2 - Amp^{-1}\}^{1/2}]\!]^{-1} . \quad (4)$$

Let us now express these quantities in function of observable quantities. For a given giant arc having a length L and a thickness w (width), the magnification factor is: $Amp = 4Lw/(\pi d_s^2)$, where d_s is the intrinsic source diameter. Then the source size could be deduced from the thickness through a power expansion of (w/L):

$$d_s = 2w[1 - K(\text{arc})][1 - \pi w/(4L)] , \quad (5)$$

where $K(\text{arc}) = 4\pi G/c^2 D_d D_{ds}/D_s \sigma(\text{arc})$, is due to the total surface density at the arc location, $\sigma(\text{arc})$. For a given gravitationally distorted image, the magnification factor becomes (surface brightness is unaffected by lensing)

$$Amp = L/(\pi w)[1 - K(\text{arc})]^{-2}[1 + \pi w/(2L)] . \quad (6)$$

These formulae stand for gravitationally distorted images for which $L \gg w$, which is obviously the case for giant luminous arcs. It comes out that for a given arc, the size of the source that one can derive from the arc thickness depends only on the surface density of the total lensing mass at the arc location, i.e., $\sigma(\text{arc})$. Figure 1 shows the different predictions from various density profiles for spherical lensing clusters. For a constant source size, the more concentrated to the cluster center the mass is, the thinner the arc is. Relation (5) implies that a $r^{1/4}$ surface density profile or point mass profile ($K = 0$) creates arcs 2 times thinner than the ones formed by a singular isothermal profile ($\rho = \rho_0 r^{-2}$, $K = 0.5$) and 4 times thinner than the ones formed by a lensing cluster described by an isothermal profile $\{\rho = \rho_0[1 + (r/r_c)^2]^{-1}\}$ with $r_c \approx 100$ kpc ($K \approx 0.75$). For a generalized Hubble profile $\rho = \rho_0[1 + (r/r_c)^2]^{-\beta}$, Figure 1*b* and relation (5) discriminate the flat density profile ($\beta \leq 2$ and $K \geq 0.5$) from the other profiles including the one deriving from the $r^{1/4}$ law.

At first approximation the critical line (infinite magnification line) can be set by the observations and then the lensing mass needed to account for a giant arc. It is shown here that the source properties (size and luminosity) are strongly dependent on the value of the lensing matter term (K). If one can put a limit on $\sigma(\text{arc})$—through conditions on the source properties—one will be able to constrain the density profile independently of any hypothesis on the nature of the matter that causes the arcs.

3. NATURE OF THE ARC SOURCES

Let us summarize the intrinsic properties of the sources of thin and luminous arcs (see also Table 1):

Most of them have spectra similar to the ones of faint spiral galaxies found in deep redshift surveys (BES; CETH; LCG) up to $B = 24$, i.e. [O II]λ3727 sometimes supported by a detection of the 4000 Å break. Secure redshift estimations lead to an average $z = 0.8 \pm 0.1$.

Their colors (see Table 1) are compatible with unevolved or passively evolved spiral Sb to Sdm or even irregular galaxies in the visible band ($0.5 \leq B - R \leq 1.9$), while preliminary results suggest they are rather red in IR-visible color index (Ellis 1989; Aragon-Salamanca & Ellis 1989), $R - K \approx 3$–4, which could be typical for star-forming spiral galaxies.

Their blue surface magnitudes μ_B range from 24 to 25 mag arcsec^{-2}. Sources with z ranging from 0.7 to 0.9 could be easily compared with nearby galaxies since their R photometry is indeed what we would have measured in the blue broadband at rest-frame. They are intrinsically very bright and their average surface brightness at rest, $\langle\mu_{B0}\rangle = 21.1$ (Table 1), equals the central surface brightness of nearby face-on spiral galaxies (Freeman 1970).

I then stress that the sources of the giant thin and luminous arcs are probably spiral or irregular galaxies at $z \geq 0.7$ similar to the galaxy population prevailing in spectroscopic surveys up to $B = 22.5$ and $\langle z\rangle = 0.32$. They fall near caustics curves of the lensing clusters, and then they should belong to a relatively numerous population at such z since the probability of one event is as low as 10^{-5}–10^{-6}. Their intrinsic surface brightnesses imply that deep surveys up to $\mu_B = 28$–29 (LCG; Tyson

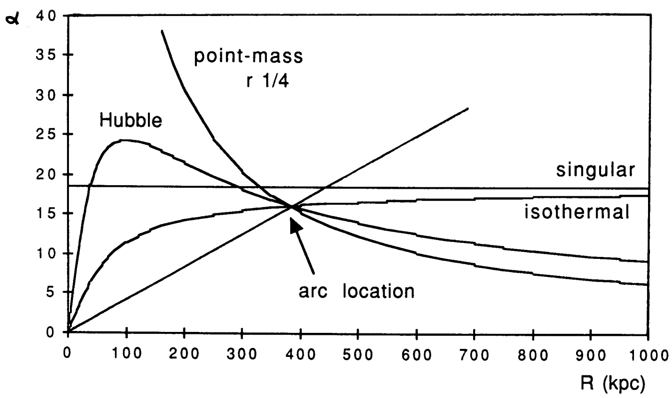

FIG. 1a

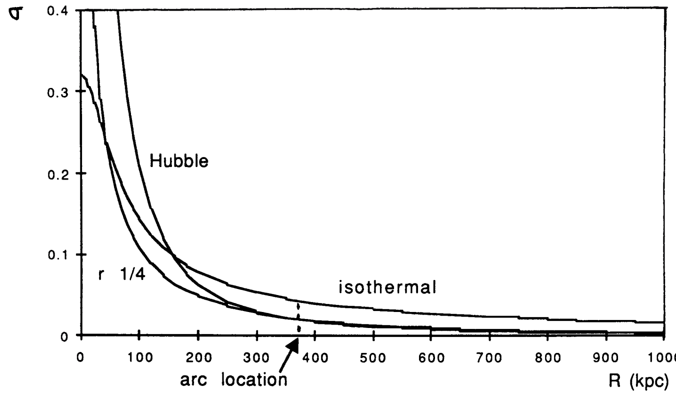

FIG. 1b

FIG. 1.—Several kinds of density profiles for a spherical lensing cluster. Hubble and isothermal profiles are assumed to have the same core radius, $r_c = 50$ kpc. An effective radius of 1 Mpc is used for $r^{1/4}$ law. Figure 1a shows the deflecting angle α vs. the radius towards cluster center. The deflecting angle decreases with radius for point-mass, $r^{1/4}$ and Hubble profile (outside the core), while it increases for isothermal profile ($K \geq 0.5$) towards the singular isothermal value (constant angle, $K = 0.5$). These profiles were chosen to cross at a common value (which is provided by $\sigma = 1000$ km s^{-1} for the isothermal profile and $M = 1.5 \times 10^{14} M_\odot$ for the point mass). The lensing equation relates the angular location of the image $\theta = R/D_d$ to the angular location of the virtual source, ϕ. The latter is nearly 0 for large magnification events and the lensing equation becomes $\theta = \alpha D_{ds}/D_s$, a straight line in this diagram. This illustrates a cluster similar to A370 acting as a lens on a source at very large z. The arc radius is ≈ 400 kpc, and could be due to several density profiles. Fig. 1b presents the corresponding surface density: the more compact density profile the lower is the surface density profile at the arc location. Here the surface density derived from the isothermal profile is twice its value derived from the Hubble or $r^{1/4}$ profile.

1988; Cowie et al. 1991) should have already caught this population of sources. In fact their color indices lie in the bulk of the color histogram derived from these surveys.

4. PRELIMINARY TESTS OF THE LENSING MASS DISTRIBUTION

Most or all of faint sources are found spatially extended (LCG; Tyson 1988; Cowie et al. 1991)—even their minor axis might be resolved—down to sizes $\approx 0''.5$ (FWHM) under seeing conditions from $0''.8$ to $1''.2$ (LCG; Cowie et al. 1991). Indeed a careful examination of ≈ 40 $B \leq 26$ galaxies in one SSA field shows that all galaxies but two are well resolved (Cowie 1991, private communication). The average value of the first moment of light distribution for these galaxies is $0''.67 \pm 0''.2$, after removing a stellar profile, which has been built from stars selected only by their colors. Arc sources would likely be $B \leq 26$ galaxies if they were unlensed. Under similar seeing conditions and from deep images made at the largest telescopes, the giant arcs are obviously thin, most of them being hardly or not resolved (see Table 1). These images were sensitive down to $\mu_B = 26.5$ mag arcsec^{-2}, and the arc width (FWHM, after removing a stellar profile) may be compared to the first moment of the light distribution of field galaxies. For an arc hardly resolved or unresolved in thickness (FWHM, w less than $0''.6$), formula (5) yields: $K(\text{arc}) \leq 0.5$.

This limit likely stands for one arc found in A370 (A5), in A963 and in Cl2244−02, which have stellar luminosity profiles along their width down to $\mu_B = 27$ mag arcsec^{-2} (Hammer et al. 1988; Angonin, Hammer, & Lavery 1991). Even for the thicker gravitationally distorted images found in A370 (A0), in Cl0024+16 and maybe for the one in Cl0500−24 the $\leq 1''$ FWHM thickness are compatible with $K(\text{arc}) \leq 0.75$. These limits are obviously preliminary and should be confirmed in the future by deep images of the arcs and of a large sample of field galaxies under very high spatial resolution. It could be difficult to reconcile the isothermal profile for rich clusters with the observations of spatially unresolved luminous arcs in their cores.

Let us investigate in more detail the intrinsic properties of the arc sources for which spectroscopy is available. One may assume that they are spirals or irregulars at $z \approx 0.8$, for which the luminosity profile follows an exponential law, $\sigma = \sigma_0 \exp(-r/r_{\text{disk}})$, and so for the luminosity profile along arc widths. If the arc thickness is estimated down to $\mu_B = 26.5$ mag arcsec^{-2}, it comes out that the characteristic disk scale of the arc source is

$$r_{\text{disk}} = 1.085[1 - K(\text{arc})]w_{26.5}(27.585 - \langle \mu_B \rangle_{26.5})^{-1} \sin\beta/\cos[\arctan(\cot\beta/\cos i)] , \quad (7)$$

where the latter term depends on the disk inclination (i) and the angle (β) between the major axis and the radial axis of the lensing cluster. The average value for this term is 0.8, a value derived from a random distribution of (i, β). All the arcs but the one in A2390 are thin ($w_{26.5} \leq 1''.5$). For $K(\text{arc}) \approx 0$ their disk scales range from 2 to 5 kpc ($50/H_0$) (see Table 1) which are usual values for moderately bright spirals (Freeman 1970). Conversely, $K(\text{arc}) \geq 0.75$ would yield disk scales smaller than 1 kpc ($50/H_0$) implying extremely compact sources for the arcs, even smaller than the SMC. This simple model yields for the arc source at rest, central surface magnitudes which range from 19.8 to 21 mag arcsec^{-2}. Arc sources are slightly brighter than nearby spiral galaxies ($\mu_B = 21.3 \pm 0.7$ mag arcsec^{-2}), which could be due either to the disk inclination or to an enhancement of the star formation as it may be suggested by the strength of the [O II] $\lambda 3727$ emission line.

Thin arc properties could be accounted for either by a population of relatively normal spiral galaxies ($K < 0.5$, $\langle Amp \rangle \approx 10$–$40$, size ≈ 5–10 kpc or disk scale ≈ 2–5 kpc, and $M_B \approx -20.5$) or by a population of very compact dwarves ($K = 0.75$, $\langle Amp \rangle \approx 160$, size ≤ 3 kpc or disk scale ≤ 1 kpc and $M_B \approx -17.5$). If the lensing clusters are not compact ($K = 0.75$), thin arcs will be linked to $L \leq 0.1$ L^* dwarves (see Table 1), and one then should detect thicker arcs corresponding to moderate magnification of more luminous and larger galaxies. These "thick" arcs might be similar to the one found

TABLE 1

MAIN PROPERTIES OF THE KNOWN GIANT LUMINOUS ARCS

Cluster	Arc	References	Arc Redshift B $B-R$	Arc Length	Arc Width (FWHM) Seeing, FWHM	Average Surface Brightness mag arcsec^{-2}, B-band	Average Surface Brightness Source at Rest	Disk Scale/$(1-K)$ (kpc, $H_0 = 50$)	L/L*, k-Corrected K(arc) $\ll 0.5$ K(arc) $= 0.5$ K(arc) $= 0.75$
A370	A0	1, 2, 3	0.72 21 1.3	22″	$\leq 0\farcs4$–$1\farcs2$ 0.7	24.4	20.7	5	0.9 0.22 0.06
	A5	3	1.3? 22.5 0.85	9	≤ 0.4 0.7	≤ 24.2	...	...	...
Cl2244−02		4, 5, 6	2.2? 21.4 1.1	19	≤ 0.5 1	≤ 24.6	≤ 17?	...	...
A963		7, 8	0.77 22 0.7	21.5	≤ 0.6 1	≤ 25.6	≤ 22	≤ 3	0.34 0.08 0.02
Cl0024+16		9	?	20	≈ 1.1 0.8	...	...	...	...
Cl0500−24		10, 11	0.91 22.5–23 ≈ 1.5	12	≈ 1 1.5	25	20.7	5	1.6 0.4 0.1
A2390		12, 13	0.92 22 1.9	15	1.5 0.7	25.8	21.1	≥ 18	10 2.5 0.8

REFERENCES.—(1) Soucail et al. 1987a; (2) Fort et al. 1988; (3) Soucail et al. 1987b; (4) Hammer et al. 1988; (5) Soucail et al. 1989; (6) Lynds & Pétrosian 1989; (7) Lavery & Henry 1988; (8) Ellis, Allington-Smith, & Smail 1991; (9) Koo 1991, private communication; (10) Giraud 1989; (11) Giraud 1990, private communication; (12) Pello et al. 1991; (13) Soucail & Fort 1991.

in A2390. For high magnification A_0, the probability $P(Amp \geq A_0)$ varies as A_0^{-2} (Turner, Ostriker, & Gott 1984). This strongly works against large magnification events and hence against small and faint sources for thin arcs. Thus the detected number of arcs $N(L)$ is given by $dN(L) \sim L^2\phi(L)dL$, where $\phi(L)$ is the galaxy luminosity function. Now assume that at $z \approx 0.8$, the shape of the galaxy luminosity function from 0.01 L* to $\approx$L* is similar to the one known at lower z ($M_B^* = -21.3$, Efstathiou, Ellis, & Peterson 1988; BES) and that all events with $Amp \geq 10$ are detectable by current imaging surveys of rich distant clusters. The arcs have magnitudes brighter than $R = 21.5$ (which is comparable to B-magnitude at rest, see also Table 1). Then, "thick" arcs (moderate magnification events on L > 0.1 L* sources) turn out to be 36 times more numerous than thin arcs (L ≤ 0.1 L*), and one-half of them would be associated with relatively bright galaxies (L ≥ 0.5 L*). However, all observed arcs but one are thin, and would be linked to L ≤ 0.1 L* sources if corresponding lensing clusters were not compact ($K \geq 0.75$). An *enormous evolution* of the luminosity function at $z \approx 0.8$ is required to reconcile "flat" density profiles with the arc observations: compact dwarves ($M_B \approx -17.5$) should be at least 200 times more abundant than moderately bright spirals ($M_B \approx -20.5$), whereas no luminosity evolution of the spiral luminosity function have been found up to $z \approx 0.4$ (BES; CETH). These compact dwarves should thus be at least 10 times more abundant than the population of dwarves recently found by Cowie et al. (1991).

I then adopt for thin arcs, the conservative limit $K \leq 0.75$ and compare the lensing mass profile with the X-ray gas profile, assuming a pseudo-Hubble profile for both. For an arc located at θ, near the critical line, the matter term at the arc location is written

$$K(\text{arc}) = X^2(1 + X^2)^{-1}[\log (1 + X^2)]^{-1} \quad \text{with} \quad X = D_d\theta/r_c . \tag{8}$$

Note that this relationship does not depend on the source redshift. It comes out that $K(\text{arc}) \leq 0.5$ leads to $r_c \leq (D_d\theta)/2$ while the most conservative $K(\text{arc}) \leq 0.75$ leads to $r_c \leq 1.2\, D_d\theta$. The giant thin and luminous arcs actually draw the cores of lensing rich clusters. The lensing mass—or dark matter—distribution is then *considerably more compact* than the X-ray gas (see Table 2; X-ray core radii are from Lea & Henry 1988).

The A370 cluster is by far the most studied of these clusters. Two large arcs—A0 and A5—lie in its core, and are unresolved or partly unresolved. Isothermal density profiles—$K > 0.5$—are then unlikely for its mass profile since they generate uncomfortably small source sizes. Models based on such profile need extreme ellipticities of the mass density—axis ratio less than 0.5—to be consistent (Grossman & Narayan 1989) with the reported velocity dispersion. Lensing mass is then extremely more concentrated to the center than the X-ray gas—core radius less than one-fourth of the X-ray core radius—and even more compact than the distribution of optical galaxies which could be described by an isothermal profile with a finite characteristic radius [92 $(50/H_0)$ kpc] (Mellier et al. 1988).

On the other hand, I find no way to put similar limits from the straight and thick—$w = 2\rlap{.}''5$—image found in A2390 (see Table 1). The source is likely seen nearly edge-on because of the large velocity gradient found along the image length (Pello et al. 1991). Then the large disk scale derived from the image thickness ($r_{\text{disk}} = 18\ (1 - K)$ kpc for $H_0 = 50$) suggests high values for K(arc) as well as the derived luminosities (Table 1). Flat density profiles ($K > 0.5$) may reproduce the observations which lead to large uncertainties on the magnification factor (from 4 to more than 40) and on the derived source size (from ≤8 to 25 kpc). Indeed this elongated and straight image is likely an example of marginal lensing (Kovner 1989). This rules out any attempt to determine intrinsic properties of this source from the lensing model and/or to use it for testing cosmology (Soucail & Fort 1991).

The predictions presented above are made on the basis of pure geometrical and statistical properties of the strong lensing events. They do not depend on any assumptions about the nature of the lensing matter, which could be dynamically linked or not, baryonic or not. Let us show how strong the prediction is, simply because the source properties derived from the giant luminous arcs are extremely sensitive to a change of the lensing density profile. Assume that the lensing mass follows the X-ray gas in the two clusters, A370 and A963. The two giant arcs would lie well inside their cores providing $K(\text{arc}) = 0.97$ for both clusters. The corresponding magnification would be in the range of 10^4, and the arc sources should be ... globular clusters!

TABLE 2

CORE RADII FROM LENSING VERSUS CORE RADII FROM X-RAY OBSERVATIONS

Cluster	Core Radius from X-Ray Observations	Upper Limit from Lensing (K(arc) < 0.75)	Upper Limit from Lensing (K(arc) ≤ 0.5)
A370	100″	<30″	...
	680 kpc		
A963	81	<21	≤9″
	370 kpc		
Cl0024+16	60	<30	...

5. MINI-ARCS OR ARCLETS

On the other hand, the mini-arcs found in distant clusters (Tyson et al. 1990) have been selected in a very different way than the giant luminous arcs. Mini-arcs have surface brightnesses about 3 mag fainter and belong to a much more abundant population of sources. I then suggest mini-arc sources could be low surface brightness dwarfs similar to the ones which may prevail at $z \approx 0.4$ (LCG: Cowie et al. 1991). Indeed at $z \approx 0.8$–1, a $L_B = 0.01$ L* dwarf with $B - R \approx 0.5$ will have $B \approx 26$, a typical value for the mini-arcs. Two clusters, A1689 and Cl1409+52, have been recently imaged for mini-arcs (Tyson et al. 1990), and are as rich as or richer than the clusters providing the giant luminous arcs. A striking feature is the cutoff found at ≈150 kpc ($H_0 = 50$) in the core of Cl1409+52 ($z = 0.46$): most of the mini-arcs are found inside this radius, which is comparable to or even lower than the critical radius derived from giant luminous arcs. To reconcile this cutoff with the assumption (Tyson 1989) that sources are at $z \approx 2$–3 implies that the mass inside Cl1409+52 core should be much less than one-third of the mass in A370 core, in apparent contradiction with their similarities. On the other hand, if sources of the mini-arcs are $z \approx 0.9$ dwarfs, the cut-off outside the 150 kpc radius could be due to the dependency of the critical radius on the source redshift (see eq. [2] with $\phi = 0$) convolved with the surface-brightness cutoff of dwarfs due to cosmological dimming of 10 log $(1 + z)$ magnitudes. It may be also the result of a detection affected by seeing since the larger the impact parameter is, the thinner the arc is (see eq. [5]). In A1689 ($z = 0.18$) the larger cutoff found, 250 kpc, could be due to either the lens properties or to the fact that dwarfs ranging from $z = 0.35$ to $z \approx 1$ are less affected by seeing and cosmological dimming effects. Unfortunately this alternative limits the possibility to derive cluster density profiles from mini-arcs, since seeing and detection limit are probably dominant. However it reconciles the detection of mini-arcs with results of deep redshift surveys (BES; LCG; Cowie et al. 1991).

The estimation of the lensing mass distribution could be attempted using two different approaches: (1) by studying the giant luminous arcs which are rare events while they are bright enough to let one sample their luminosity profiles and to disentangle the lensing mass properties from source properties; (2) by searching for arclets which probably lie in the core of most of the distant clusters and allow one to sample the lensing mass density at various impact parameters, while their faintnesses prevent any attempt to deconvolve lens properties from source properties and have dominant seeing and detection limit effects.

6. DISCUSSION AND CONCLUSION

I have presented new formulae for magnification and image thickness which apply to giant luminous arcs. These quantities depend only on $[1 - K(\text{arc})]$ where $K(\text{arc})$ is lower than 0.5 for compact density profiles (point mass, $r^{1/4}$, Hubble profile with small core radius) and larger than 0.5 for flat density profiles (isothermal profile, Hubble profile with core radius derived from X-ray observations). This leads to a first attempt to deconvolve the source properties from the lensing properties. Using available data, I have shown that, either the lensing mass distribution is very compact and the sources are spiral galaxies similar to the ones found in deep spectroscopic surveys, or the lensing mass distribution is compatible with isothermal profiles, and the sources belong to a new and overwhelming population of extremely compact dwarfs lying at $z \geq 0.7$. It is much more difficult to extract similar information from multiple QSOs, since we ignore the geometry of the lensing events, i.e., length and thickness of the gravitationally distorted images.

These new formulae applied to giant luminous arcs show that source parameters are very sensitive to a change of the lensing density profile. Magnification probability strongly argues against large magnifications and hence against small and faint sources for thin arcs. Indeed if galaxies do not show enormous luminosity evolution up to $z \approx 0.8$, the mass distribution of most of the lensing clusters will be much more compact than the X-ray gas and even more compact than the light distribution. This conclusion is based on a pure geometrical and statistical argument—i.e., the arcs are thin and luminous—without any assumption about the nature of the lensing matter, which could be baryonic or not, dynamically linked or not. On the other hand, if the source of the Cl2244−02 arc was indeed at $z = 2.2$ (Soucail et al. 1989), it should be a clue for a numerous population of extremely bright galaxies (surface magnitude at rest brighter than 17 mag arcsec^{-2}!) at very high z. Deep images of giant luminous arcs and new spectroscopic measurements are wished to shed new light on these important issues.

Note added in manuscript.—Bergman, Petrosian, & Lynds (1990) have numerically calculated the relationship between the source size and the core radius of the lensing cluster, which agrees with the analytical calculation presented above. The more compact lensing cores are, the smaller the source sizes.

I would like to thank O. Le Fèvre, G. Mamon, C. Vanderriest, and X. P. Wu for discussions and for reading the manuscript of this article. I am also grateful to E. Giraud and D. Koo for communicating to me unpublished data. I am especially indebted to L. Cowie for sending me data prior to publication and for his enlightening comments.

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