ANOMALOUS FLUX RATIOS IN GRAVITATIONAL LENSES: FOR OR AGAINST COLD DARK MATTER?

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ABSTRACT

We review the evidence for substructures from the anomalous flux ratios in gravitational lenses. Using high-resolution numerical simulations, we show that at typical image positions, the fraction of surface mass density in substructures is $\lesssim 0.5\%$ with mass above $10^{-4}$ virial masses in the “concordance” $\Lambda$CDM cosmology. Substructures outside the virial radius (but projected at typical lens image positions) only increase the fraction moderately. Several effects, in particular baryonic settling and the requirement of compactness, may further decrease the predictions by a factor of few. The predicted fraction with appropriate properties thus appears to be lower than that required by lensing, although both are still uncertain. More speculative substructures such as massive black holes ($M \sim 10^{5}-10^{6} M_{\odot}$) in the halo may offer viable alternatives.

Subject headings: cosmology: theory — dark matter — galaxies: evolution — galaxies: structure — gravitational lensing

On-line material: color figure

1. INTRODUCTION

Gravitational lenses on arcsecond scales provide a unique sample to probe the mass distribution in the lensing galaxies at intermediate redshift ($z \sim 0.5$--1). Image positions in most lenses can be fitted adequately using simple smooth galaxy mass models. But observed flux ratios are more difficult to match (e.g., Kochanek 1991). The discrepancy between the predicted and observed flux ratios is commonly referred to as the “anomalous flux ratio problem.” The most apparent cases are found in quadrupole lenses where we observe a close pair or a close triple of images. Here we know that the lensed source is close to either a fold or a cusp caustic. The asymptotic magnification behavior in such cases is well understood—a close pair must have equal brightness, while for a close triple, the flux of the middle image should be equal to the total fluxes of the two outer images. Virtually all the observed pairs and triples disagree with these relations (§ 2). This has been argued as evidence for substructures on the scale of the separations of the images (a few tenths of arcseconds; e.g., Mao & Schneider 1998; Metcalf & Zhao 2002). Another piece of evidence for substructures is the fact that saddle images are preferentially dimmed compared to model predictions (Kochanek & Dalal 2003). This is expected from millilensing by substructures (Keeton 2003) or microlensing by stars (Schechter & Wambsganss 2002); such a preferential demagnification of saddle images is not expected from other propagational effects.

The cold dark matter (CDM) structure formation model predicts the existence of just such substructures from both semi-analytical studies and numerical simulations (e.g., Kauffmann et al. 1993; Klypin, Kravtsov, & Valenzuela 1999; Moore et al. 1999; Ghigna et al. 2000). Among these, seven are simple quadrupole lenses, including B1209+542 (Kochanek & Dalal 2003a; see also Koopmans et al. 2002) and B0218+437 (Phillips et al. 2000; Biggs et al. 2004). It is illustrative to see the issues using the largest homogeneous lens survey—the Cosmic Lens All-Sky Survey (CLASS; Myers et al. 2003 and references therein), with a density parameter $\Omega_{\Lambda,m} = 0.3$, a cosmologically constant $\Omega_{\Lambda} = 0.7$, and a baryon density parameter $\Omega_{b} = 0.024 h^{-2}$, and we take the power spectrum normalization $\sigma_{8} = 0.9$. We write the Hubble constant as $H = H_{0}/(100 \text{ km s}^{-1} \text{ Mpc}^{-1})$ with $h = 0.7$.

2. REQUIRED AMOUNT OF SUBSTRUCTURES FROM GRAVITATIONAL LENSES

A number of papers have discussed evidence for substructures from gravitational lenses; most concentrated on the anomalous flux ratios (e.g., Mao & Schneider 1998; Metcalf & Madau 2001; Chiba 2002; Bradac et al. 2002; Dalal & Kochanek 2002; Keeton 2003), while several papers discussed astrometric signatures, such as bent jets in B1152+199 (Metcalf 2002), and unusual VLBI structures for MG 2016+112 (Kochanek & Dalal 2003a; see also Koopmans et al. 2002) and B0126+437 (Phillips et al. 2000; Biggs et al. 2004). It is illustrative to see the issues using the largest homogeneous lens survey—the Cosmic Lens All-Sky Survey (CLASS; Myers et al. 2003 and Brown et al. 2003). This radio survey has well-defined selection criteria and does not suffer from the effect of dust extinction. Radio lenses are also not substantially affected by stellar microlensing (see Koopmans et al. 2003 and references therein).

In total, there are 22 new lenses discovered in CLASS. Among these, seven are simple quadrupole lenses, including five close pairs (B0128+437, Phillips et al. 2000; MG 0414+0534, Hewitt et al. 1992; B0712+472, Jackson et al. 1998; B1608+656, Myers et al. 1995; B1555+375, Marlow et al. 1999) and two close triples (B2045+265, Fassnacht et
complex model (e.g., with an additional shear) may be able to explain it. For B0128+437, an SIE model cannot fit the flux ratio, but the observed flux ratio can be reproduced with an additional shear. However, in this case, the relative orientations of jets in this system appear difficult to match with a smooth model (Biggs et al. 2004), so substructures may yet be called for. For the two close triple lenses, the flux ratios appear difficult to match with smooth models (Mao & Schneider 1998; Fassnacht et al. 1999; see also Keeton, Gaudi, & Petters 2003).

Mao & Schneider (1998) showed that substructures preferentially affect the flux ratios of highly magnified images. In order to reproduce the flux ratios in B1422+231, they found that the required perturbation in the dimensionless surface mass density, \( \delta \kappa/\kappa \), is of a few percent and roughly corresponds to a physical surface density of a few tens \( M_\odot \) pc\(^{-2} \). Dalal & Kochanek (2002) performed a statistical study of seven radio lenses using Monte Carlo simulations, six of which show anomalous flux ratios. They find that the fraction of mass required in substructures should be in the range of \( f_{\text{sub}} = 0.6\%–7\% \) (90% confidence limit) with a best fit of \( f_{\text{sub}} \approx 2\% \). More recently, Metcalf et al. (2004) applied the method of Moustakas & Metcalf (2003) to the quadrupole system 2237+0305. They conclude that in order to match the observed flux ratios in the radio, infrared, and narrow and broad emission lines, 4\%–7\% of the surface mass density (95% confidence limit) must be in substructures with mass between 10^4 and 10^9 \( M_\odot \).

3. PREDICTED SUBSTRUCTURES IN NUMERICAL SIMULATIONS

We use the high-resolution halo simulations of Jing & Suto (2002, 2000) to constrain the fraction of mass in substructures; similar results (but with larger error bars) are found using the simulation data obtained with the tree particle-mesh code of Bode & Ostriker (2003). Twelve halos were selected from a cosmological simulation of a box of 100 \( h^{-1} \) Mpc, with four each at galactic, group, and cluster masses, respectively. These simulations are evolved with a nested-grid PPPM code that was designed to simulate high-resolution halos. The force resolution is typically 0.004\( r_{\text{vir}} \), where \( r_{\text{vir}} \) is the virial radius. At the end of each simulation, about (0.5–1) \( \times 10^7 \) particles are within \( r_{\text{vir}} \) of each halo (see Jing & Suto 2000 for details).

We adopt the SUBFIND routine of Springel et al. (2001) to find disjoint self-bound subhalos within a parent halo. All subhalos with more than 10 particles are included in our analysis. Our numerical resolution implies that we can only identify subhalos with mass larger than about 10^4 of the parent halo mass; the most massive subhalo has about 10% of the parent halo mass. For each halo, we make 30 random projections and calculate the total mass within different annuli; the annuli are spaced in \( \log (r/r_{\text{vir}}) \) from -2.2 to 0 with a step size of 0.2, where \( R \) is the projected radius and the spherical radius is \( r_{\text{vir}} \). The total mass in substructures within an annulus is calculated by summing up all the mass of subhalos whose centers fall in it. Dividing the total substructure mass by the total mass within the annulus yields the fraction of the projected surface density in substructures, \( f_{\text{sub}} \). The mean value and variance of \( f_{\text{sub}} \) are found from the 12 halos and the 30 random projections. In the top left panel of Figure 1, we show \( f_{\text{sub}} \) as a function of \( R/r_{\text{vir}} \). The mean fraction can be approximated as \( f_{\text{sub}} \approx 0.25(R/r_{\text{vir}}) \). The scatter around the mean among halos is quite large. At \( R \approx r_{\text{vir}} \), the scatter is about 40%; at smaller \( R \) the scatter is larger because of fewer subhalos along the line of sight. As lensing concerns only the projected surface density, we also checked whether substructures outside the spherical virial radius can contribute to the surface density at a given \( R \).
dark matter is consistent with that required by stellar micro-

effect by Chen et al. (2003).

Almost all subhalos in the simulation have a spherical radius
and triples in quadruple lenses. As emphasized by Ko-

For the five systems, we find that the stellar component
20%–50% of the projected surface density

If the lens and source redshifts are known, then the separation

Most substructures at typical image positions \( R \approx 0.01 r_{\text{vir}} - 0.03 r_{\text{vir}} \) only appear along the line of sight due to

If the lens and source redshifts are known, the separation

\( r_{\text{vir}} \sim 0.03 r_{\text{vir}} \) for each subhalo.

The lens and source redshifts are known for MG 0414 + 0534,

For the five sources with known lens and source redshifts

\( V \approx 2 \sigma \), which in turn allows us to determine the

The lens and source redshifts are known for MG 0414 + 0534,

\( 0.01, 0.006, \) and 0.012, respectively. We take (appropriate for a

So far we have only considered the fraction of dark matter

\( r_{\text{cool}} \) is within 0.025 \( r_{\text{vir}} \) for each subhalo.

The lens and source redshifts are known for MG 0414 + 0534,

\( B1555 + 375. \) For these systems, the image positions in units of the virial radius

\( 0.027, 0.012, 0.018, 0.017, \) and 0.012, respectively. From

Figure 1 we can then infer that the fraction of mass in sub-

Figure 1, bottom panels). We return to this compactness issue in

To compare the predicted fraction with lensing requirement

We have reviewed the evidence for substructures from close

(4, \( Q/0 \)). The fraction of surface mass density in

\( \lesssim 0.100 \text{ km s}^{-1} \) seem to be too concentrated compared with

observed galaxies (e.g., Bolatto et al. 2002; Weldrake et al.

However, there are a number of issues that need to be understood

The SUBFIND algorithm that we adopted only identifies

and contributes about 20%–50% of the projected surface density

These subhalos, especially those at \( r \sim r_{\text{vir}} \), are extended,

\( \approx 0.2\%–0.8\% \), with a large scatter among different halos.

So far we have only considered the fraction of dark matter

surface density in substructures. However, the inner parts of
galaxies are likely dominated by baryons. To address this issue,

\( M_{\text{cool}} \) and \( r_{\text{cool}} \) are related by the concentration parameter

For the five sources with known lens and source redshifts

\( c = 10 \) (appropriate for a

galactic-sized halo) and then carry out the procedure described

For the five systems, we find that the stellar component

\( 0.05 \) to 0.16 \( (\lesssim \Omega_{\Lambda}/\Omega_{0}) \). The fraction of surface mass density in

dark matter is consistent with that required by stellar micro-
lensing \( (\approx 70\%–90\% \) at 1.5 \( r_{\text{vir}} \), Schechter & Wambsganss 2004)

but at odds with the recent claim of Romanowsky et al. (2003).

The effect of baryons hence reduces the mass fraction in sub-
structures in typical lensing systems to \( \lesssim 0.5\% \).

4. DISCUSSION

We have reviewed the evidence for substructures from close
pairs and triples in quadruple lenses. As emphasized by Ko-
chanek & Dalal (2003b), the fact that saddle images are fre-
quently dimmer than expected is difficult to accommodate by

other means. Quantitatively, the anomalous flux ratios in lenses
appear to require a few percent of the surface mass density in
substructures at typical image positions (Dalal & Kochanek
2002; Metcalf et al. 2004). The required fraction is higher than

that provided by globular clusters and luminous satellite gal-
axies (Mao & Schneider 1998; Chiba 2002), and it also appears to
be higher than the predicted values \( f_{\text{sub}} \lesssim 0.5\% \) from the
\( \Lambda \text{CDM} \) cosmology at typical image positions. However, at
present it is unclear how serious the discrepancy is because of
uncertainties in both observations and theoretical predictions.

There are a number of issues that need to be understood

better in current numerical simulations. Even the basic question

of the identification of substructures needs to be explored fur-
ther. The SUBFIND algorithm that we adopted only identifies

bound subhalos; however, tidal streams from disrupted systems

(for example in the Milky Way; see, e.g., Ibata et al. 2001; Yan-
ny et al. 2003) may also contribute to the budget of sub-
structures. Another important issue is whether our results have
achieved convergence as a function of the spatial and mass
resolutions. New simulations are underway to address this is-

sue. Presumably when the numerical resolution becomes higher,

the inner parts of subhalos are resolved better into higher den-
sity regions that can survive tidal disruptions longer. However,

the survival of substructures may be linked to another small-

scale problem of CDM: the central density profiles of low

surface brightness galaxies (usually with circular velocities

of \( \approx 100 \text{ km s}^{-1} \)) were too concentrated compared with

observed galaxies (e.g., Bolatto et al. 2002; Weldrake et al.

2003; see, however, Swaters et al. 2003). Therefore, if we put

in observed mass profiles, substructures may actually be more
easily destroyed by tidal forces because of their lower central

concentrations. There is another effect that makes the survival

of substructures in the central part more difficult. In collision-

less numerical simulations, the density profile can be approx-
imated by an NFW profile; the density scales as proportional

to \( r^{-1} \) out to \( \sim 0.1 r_{\text{vir}} \) \( \sim 25 \text{ kpc} \) for typical galactic-sized halos.

However, the observed velocity dispersion is nearly constant

in the inner part implying \( \rho \propto r^{-2} \), i.e., the density in real
galaxies rises more quickly as the radius decreases. Hence sub-
structures will be disrupted more easily if they come close to
the center, and dynamical frictions dragging them into the cen-
ter would also be larger in realistically simulated galaxies.

Our simulations resolve substructure masses from \( 10^{5} \) to

\( 10^{11} M_{\odot} \) for a \( 10^{12} M_{\odot} \) parent halo. However, according to

Metcalf et al. (2004), the required substructure mass is in the

range of \( 10^{6}–10^{8} M_{\odot} \) in the case of 2237+0305. If the mass
spectrum of substructures \( n(M) dM \approx M^{-3} dM \) extends all the way
down to \( 10^{5} M_{\odot} \), one can estimate that the fraction of

mass in substructures with \( 10^{5} M_{\odot} < M < 10^{8} M_{\odot} \) is about a factor
of 3 smaller than that in substructures with \( 10^{8} M_{\odot} < M <
10^{11} M_{\odot} \), i.e., the mass fraction in substructures in the range
required by Metcalf et al. (2004) will be even lower than

our predicted value. This conclusion depends on the mass spec-
trum. However, for any power-law spectrum with a slope
shallower than \( -2 \), the mass fraction in substructures with
\( 10^{5} M_{\odot} < M < 10^{8} M_{\odot} \) is likely smaller than that in higher
mass substructures identified in numerical simulations.

There is another effect that may reduce the utilizable mass
in substructures even further: the need for compactness, an issue

that we already touched on in § 2 (see Fig. 1). In order to

affect the flux ratios significantly, the physical size of sub-
structures must be sufficiently compact (cf. Metcalf et al. 2004).
The most efficient substructures should be of the same order.
of the image separation of the pairs or triples. For the five CLASS quadrupole lenses that have known lens and source redshifts (see § 4), the closest pairs have projected separations from 0.6 h−1 kpc (for B1422+231) to 2.3 h−1 kpc (for MG 0414+0534). At redshift of 0.5, dark matter halos with \( M \leq 4 \times 10^6 M_\odot \) will have \( r_{\text{vir}} \approx 1 h^{-1}\text{kpc} \), and so they will be efficient in causing flux anomalies if they are located between close pairs or triples. For larger masses, the effect is reduced. We estimate the reduction by assuming that only the mass enclosed within 1 h−1 kpc will affect the flux ratios. We adopt a mass spectrum for dark matter halos of

\[
\frac{dn(M)dM}{M} \propto M^{-1.5} dM \text{ for } 10^7 M_\odot < M < 10^{11} M_\odot.
\]

Each halo is described by an NFW profile with a concentration parameter given by \( c \approx \frac{1}{12^{1/3}} h^{-2/3} M_\odot \) (e.g., Zhao et al. 2003). Note that the substructures in the central parts are tidally truncated and so cannot be fitted well by NFW profiles, but as most substructures have in spherical radius, the effect of tidal truncation may be modest. We find that the mass in substructures that can efficiently cause flux anomalies is reduced by an additional factor of 5 compared with the total mass in all substructures—most substructures that are in the outer parts are too extended to cause flux anomalies efficiently. Our rough estimate shows that the compactness requirement is an issue that needs to be addressed more carefully. The two additional effects noted can reduce the likely mass fraction in substructures having the required masses and sizes to as low as ≈0.03%, uncomfortably low compared with the observational requirement.

Progress can be made from both the observational and the theoretical fronts to reduce the uncertainties. Observationally, in the radio, the effect of scattering can be studied with observations at high frequency where it is expected to be unimportant. In the infrared, it would be interesting to have more observations with integral field spectroscopy similar to that reported by Metcalf et al. (2004). This method offers a way to separate stellar microlensing from substructure millilensing. More astrometric signatures of substructures will be important as well (see § 2). Theoretically, higher resolution simulations are needed and are already underway. If future observations and numerical simulations still indicate a discrepancy between lensing requirements and CDM predictions, then alternatives must be sought. One possibility is that these substructures are massive black holes with \( M \sim 10^5-10^6 M_\odot \) (Lacey & Ostriker 1985; Xu & Ostriker 1994), which satisfy the mass and compactness requirements. We require only a few percent of the surface density in the substructures, so the density parameter in these black holes is only \( f_{\text{sub}} \omega \sim 0.012 f_{\text{sub}}/0.04 \), which is about 30%\((f_{\text{sub}}/0.04)\) of the baryon density in the universe. These massive black holes will have other observable signatures (e.g., Wambsganss & Paczyński 1992; Tremaïe & Ostriker 1999) and can be further tested.

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REFERENCES

Biggs, A., et al. 2004, MNRAS, in press (astro-ph/0402128)
Bode, P., & Ostriker, J. P. 2003, ApJS, 145, 1
Bolatto, A. D., Simon, J. D., Leroy, A., & Blitz, L. 2002, ApJ, 565, 238
Bradac, M., Schneider, P., Steinmetz, M., Lombardi, M., King, L. J., & Porcas, R. 2002, A&A, 388, 373
Browne, I. W. A., et al. 2003, MNRAS, 341, 13
Chen, J., Kravtsov, A. V., & Keeton, C. R. 2003, ApJ, 592, 24
Chiba, M. 2002, ApJ, 565, 17
Dalal, N., & Kochanek, C. S. 2002, ApJ, 572, 25
Evans, N. W., & Witt, H. J. 2003, MNRAS, 345, 1351
Fassnacht, C. D., & Lubin, L. 2002, AJ, 123, 627
Fassnacht, C. D., et al. 1999, AJ, 117, 658
Ghigna, S., Moore, B., Governato, F., Lake, G., Quinn, T., & Stadel, J. 2000, ApJ, 544, 616
Hewitt, J. N., et al. 1992, AJ, 104, 968
Ibata, R., Irwin, M., Lewis, G. F., & Stolte, A. 2001, ApJ, 547, L133
Jackson, N. J., et al. 1998, MNRAS, 296, 483
Jing, Y. P., & Suto, Y. 2000, ApJ, 529, L69
———. 2002, ApJ, 574, 538
Kauffmann, G., White, S. D. M., & Guiderdoni, B. 1993, MNRAS, 264, 201
Keeton, C. R. 2001, ApJ, 561, 46
———. 2003, ApJ, 584, 664
Keeton, C. R., Gaudi, B. S., & Petrers, A. O. 2003, ApJ, 598, 138
Klypin, A., Kravtsov, A. V., & Valenzuela, O. 1999, ApJ, 522, 82
Kochanek, C. S. 1991, ApJ, 373, 354
Kochanek, C. S., & Dalal, N. 2003a, in IAU Symp. 220, Dark Matter in Galaxies, ed. S. D. Ryder, M. A. Walker, D. J. Pisano, & K. C. Freeman (San Francisco: ASP), in press (astro-ph/0309163)
Springel, V., White, S. D. M., Tormen, G., & Kauffmann, G. 2001, MNRAS, 328, 726
Stoehr, F., White, S. D. M., Tormen, G., & Springel, V. 2002, MNRAS, 335, L84
Swaters, R. A., Madore, B. F., van den Bosch, F. C., & Balcells, M. 2003, ApJ, 583, 732
Tremaine, S., & Ostriker, J. P. 1999, MNRAS, 306, 662
Wambsganss, J., & Paczyński, B. 1992, ApJ, 397, L1
Wielebinski, R. P., de Blok, W. J. G., & Walter, F. 2003, MNRAS, 340, 12
Xu, G., & Ostriker, J. P. 1994, ApJ, 437, 184
Yanny, B., et al. 2003, ApJ, 588, 824
Zhao, D. H., Jing, Y. P., Mo, H. J., & Boerner, G. 2003, ApJ, 597, L9