

Small-Scale Structure, Missing Galaxies and Gravitational Lensing

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Abstract. The gravitational lensing constraints on the small mass end of the Λ CDM mass function are discussed. Here a conservative approach is taken where the most difficult to explain image flux anomalies in strong lenses are emphasized. Numerical simulations are performed to compare predictions for the Λ CDM small scale mass function with the observed flux ratios. It is found that the cusp caustic lens anomalies and the disagreements between monochromatic flux ratios and simple lens models can be explained without any substructure in the primary lenses' dark matter halos. Extragalactic Λ CDM halos are enough to naturally explain these cases. This does not mean that substructure within the host lens is not contributing. In fact, it could be dominating the lensing. It should also be noted that this extragalactic population has not been directly observed either.

Spectroscopic gravitational lensing provides more information on the nature of these substructures. In the one relevant case in which this technique has been used so far, observations of Q2237+0305, there is evidence that there are more small mass halos ($\sim 10^6 M_\odot$) than is expected in the Λ CDM model.

1. Introduction

The Cold Dark Matter (CDM) model predicts a large quantity of small mass dark matter halos ($\lesssim 10^7 M_\odot$) that must have little or no stars in them to agree with the number counts of dwarf galaxies. Quasars (QSOs) that are being gravitationally lensed into multiple images have recently been used to put limits on the surface density and mass of such invisible subclumps (Mao & Schneider 1998, Metcalf & Madau (2001), Chiba 2002, Metcalf (2002), Metcalf & Zhao 2002, Dalal & Kochanek 2002, Bradač, *et al.* 2002, Keeton 2003, Metcalf, Moustakas, Bunker, & Parry 2004). The question arises as to whether these observations are reliable and compatible with the current Λ CDM model.

Some lenses provide much stronger and more certain constraints on the small scale structure than others. I try to take a conservative approach here and consider only the lenses that provide clean, relatively unambiguous constraints. The standard Λ CDM cosmological model will have the cosmological parameters $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, $\sigma_8 = 0.9$, $H_o = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and a scale free initial power spectrum.

2. Some Background

There are essentially four ways that have been proposed for detecting substructure in multiply imaged QSO lenses. They are briefly described here.

2.1. Monochromatic magnification ratio anomalies

It was proposed by Metcalf & Madau (2001) that the missing CDM substructure could be searched for by comparing the flux ratios of 4-image QSO lenses with those predicted

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by lens models. Simulations showed that if the substructure has a small mass scale the image positions can be used to constrain the host, smooth lens model. It was subsequently shown that the magnification ratios of observed lenses generically do not agree with simple lens models (Metcalf & Zhao 2002, Chiba 2002, Dalal & Kochanek 2002). These anomalies are probably the result of substructure (see Kochanek & Dalal 2003 for some arguments), but in interpreting the results degeneracies in the lens models become a problem. More complicated lens models can fit the image positions just as well and give different predictions for the magnification ratios. To actually measure properties of these substructures a more precise method is required.

2.2. *The cusp caustic relation*

It can be shown that if the source is close to a cusp in the caustic of a sufficiently smooth lenses three of the images will be clustered together and the magnifications of the close triplet will sum to zero; taking the parity reversed images to have negative magnification (Schneider & Weiss 1992). To make this prediction independent of the intrinsic luminosity of the QSO the images in the triplet are labeled A through C and the cusp caustic parameter, R_{cusp} , is defined as

$$R_{\text{cusp}} \equiv \frac{\mu_A + \mu_B + \mu_C}{|\mu_A| + |\mu_B| + |\mu_C|} \quad (2.1)$$

which should be zero if the lens map is sufficiently smooth. Small scale structure on approximately the scale of the image separations will cause R_{cusp} to differ from zero fairly independently of the form of the rest of the lens (Mao & Schneider 1998, Keeton, Gaudi, & Petters 2003).

The five well observed cusp caustic lenses all show violations of the magnification relation at some level. Two of these are only measured in the optical/near-IR where microlensing by stars could be important. The three with R_{cusp} measured in the radio (B0712+472, B2045+265 and B1422+231) clearly violate the relation although B1422+231 is less clear than the others. In section 4 (and in Metcalf (2004), Amara, Metcalf, & Cox 2004) the significance of these violations is investigated.

2.3. *Spectroscopic gravitational lensing*

It was proposed by Moustakas & Metcalf (2003) that much of the lens model degeneracy can be removed and the sensitivity to substructure properties improved by utilizing the fact that the different emission regions of the source QSO have different physical sizes. If the lens is smooth on the scales that bridge the sizes of the emission regions, the magnification of those regions should be the same and thus the magnification ratios should be the same. The visible and near-infrared (near-IR) continuum emission regions are small (~ 100 AU) and their magnification can be affected by microlensing by ordinary stars in the lens galaxy. The broad line emission region is ~ 0.1 pc in size and is less affected by microlensing in most cases. The radio and mid-IR regions are ~ 10 pc; their magnification will be dominated by larger scales than stars. The narrow line emission region is even larger, $\gtrsim 100$ pc. The magnification ratios in these bands and lines can be compared to constrain the mass, concentration and number density of substructures. Metcalf, Moustakas, Bunker, & Parry 2004 found that the narrow line magnification ratios do not agree with the radio and mid-IR ratios (although the radio and mid-IR ratios do agree with each other) in the lens Q2237+0305. It was shown in that paper that at least a few % of the surface density of the lens needs to be in substructure of mass $\lesssim 10^7 M_{\odot}$ to explain this mismatch. This result is not consistent with the present Λ CDM predictions in that it requires too much mass in very small mass halos either

inside the lens of somewhere along the line of sight. However, these predictions could be significantly underestimating the amount of substructure because of numerical effects in the simulations (see J. Taylor, these proceedings).

2.4. Bent radio jets

It is also possible to look for substructure by comparing the curvature, on milliarcsecond scales, of multiply imaged radio jets (Metcalf & Madau (2001)). There is some evidence that the bends in the jets of B1152+199 are not compatible with a smooth lens, but the case is not yet water tight (Metcalf (2002)).

3. Simulations

Numerical simulations are necessary to calculate the expected influence of small scale structure on the magnification ratios. Generally there are multiple small halos affecting a single image, the size of the source (in the radio, mid-IR or narrow lines) is significant compared to the sizes of the substructures and the effect of a single substructure on multiple images must be considered. Any massive object near the line of sight inside or outside of the primary lens could potentially contribute. Both contributions have been simulated, but here we concentrated on the extragalactic part. The simulation method is more thoroughly discussed in Metcalf (2004). Here it is briefly outlined.

The large number of small halos and the large range in size scales, from the size of the primary lens (~ 100 kpc) to the size of the source ($\lesssim 0.1$ pc for the broad line emission region), make finding the images and calculating magnifications challenging and time consuming. An adaptive mesh refinement technique is used to overcome these problems. The entire lens is simulated at once in all cases.

For extragalactic halos the Press & Schechter (P&S) formalism is used to calculate the mass function from which a random sample of halos is drawn. In this mass regime the P&S mass function differs very little from the Sheth & Tormen mass function. The structure of these halos is taken to be of the NFW form truncated at the virial radius. The initial power spectrum is taken to be scale invariant and normalized to $\sigma_8 = 0.9$. The concentrations of the halos are set according to

$$c = c_o \left(\frac{M}{10^{12} M_\odot} \right)^{-\beta} \quad (3.1)$$

with $c_o \simeq 12$ and $\beta = 0.13$, in agreement with Zentner & Bullock 2003. In addition to the substructure, a model for the host lens must be chosen. The lensing results can change significantly when β or σ_8 is changed. A SIE + external shear model is used in these simulations.

4. Results of simulations

Simulations were performed to mimic the observed lenses with the addition of Λ CDM halos. The resulting combinations of image magnifications are then compared with those observed to determine if the observed anomalies are expected to be reasonably common in this cosmological model or unlikely.

To represent lenses in the Einstein cross configuration, a host lens model is constructed that fits the image positions of Q2237+0305. The effects of substructure within the host lens and its contributions to *spectroscopic lensing* were investigated in Metcalf, Moustakas, Bunker, & Parry 2004. Only the extragalactic contribution to *monochromatic* magnification ratios is discussed here.

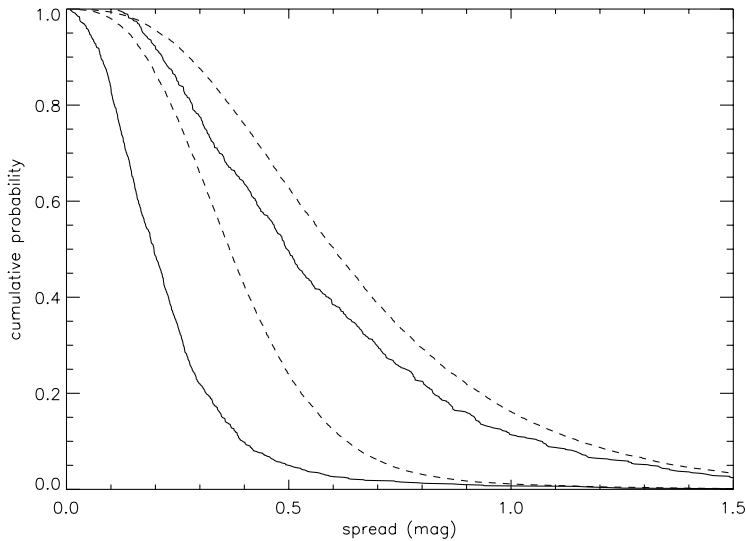


Figure 1. This is the probability of having a magnification ratio disagree with the lens model by more than a certain magnitude for Q2237+0305. The two solid curves are without observational noise and the dashed curves are with 0.15 mag of noise. For each type of curve the one on the left is for extragalactic halos with $10^7 M_{\odot} < m < 10^8 M_{\odot}$ and the one on the right is for $10^7 M_{\odot} < m < 10^9 M_{\odot}$. There is no substructure inside the primary lens.

Figure 1 shows a cumulative distribution of the largest discrepancy (in magnitudes) between the smooth model predictions and simulated values for the three magnification ratios. The source size is 1 pc in this case. Most of the anomalies are caused by the high end of the mass distribution, $m \simeq 10^8 - 10^9 M_{\odot}$. One can see that these discrepancies are rather large even without any substructure in the host lens itself – discrepancies as large as ~ 0.5 mag are expected in half the cases. The typical discrepancies between observed flux ratios and models are a few tenths of a magnitude (see Metcalf & Zhao 2002, Kochanek & Dalal 2003). This makes the observed *monochromatic* ratio anomalies consistent with Λ CDM, simple lens models and no substructure internal to the primary lenses.

Λ CDM halos seem easily capable of changing the monochromatic magnification ratios by this much, but they do not produce the mismatch in the magnifications of different size sources as seen by Metcalf, Moustakas, Bunker, & Parry 2004. This problem can be traced to a deficiency of small mass ($\sim 10^6$) halos in the Λ CDM model.

To investigate violations of the cusp caustic relation simulations were done for several models designed to mimic observed lenses. Figure 2 shows the distribution of R_{cusp} for B1422+231 with the expected population of extragalactic halos only. The first thing to note is the marked asymmetry in the distribution. As previously seen (Metcalf (2001), Metcalf & Madau (2001), Schechter & Wambsganss 2002), the magnifications of negative magnification images are affected by substructure differently than positive magnification images. When substructure is added, R_{cusp} is biased toward positive values.

Also shown in figure 2 is the observed value of R_{cusp} for comparison. There is a perfectly reasonable probability of $\simeq 0.28$ that R_{cusp} would be even larger than the observed value. By comparing the two different ranges for the halo masses, it can be seen that violations in the cusp caustic relation are mostly caused by more massive halos in this case. In light

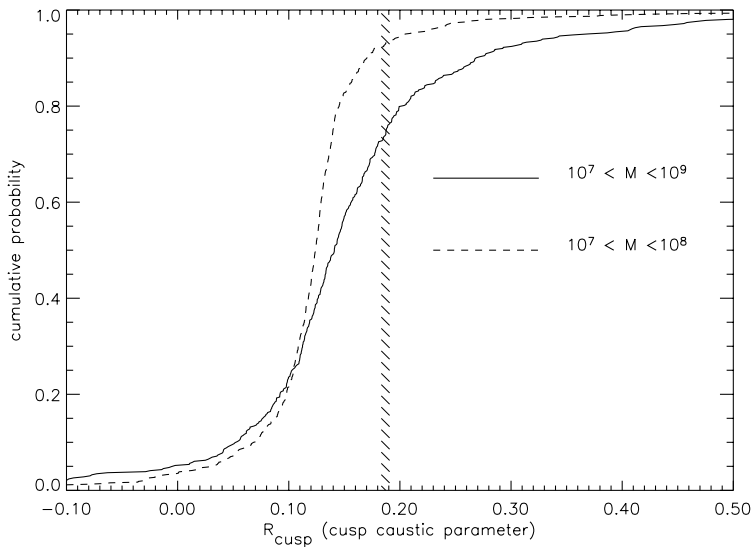


Figure 2. The distribution of the cusp caustic parameter, R_{cusp} , for lens B1422+231 with only extragalactic standard Λ CDM small-scale structure. The observed value in the radio with error is shown as the hashed region. The different curves correspond to the halo mass ranges shown. It can be seen that most of the changes in R_{cusp} are caused by relatively large mass halos, $10^8 M_{\odot} < m < 10^9 M_{\odot}$. There is about a 25% chance of R_{cusp} differing from zero by more than is observed.

of this, the violation of the cusp caustic relation in B1422+472 seems fully consistent with the Λ CDM model even without substructure within the halo of the primary lens.

We can also compare figure 2 to lens B0712+472 which has a similar configuration to B1422+231 although a lower source redshift. It is easily seen that its value of $R_{\text{cusp}} = 0.26 \pm 0.02$ is not particularly unlikely (there is a $\sim 12\%$ probability of it being larger) and thus does not require an additional explanation beyond the expected population of extragalactic halos.

Lens B2045+265 is a more extreme cusp caustic case. Figure 3 shows the results for simulations with just extragalactic Λ CDM halos. With a halo mass range of $10^6 M_{\odot} < m < 10^9 M_{\odot}$ the observed R_{cusp} does not appear strongly disfavored – 15% chance of it being larger. Considering the additional substructure within the host lens, the observed R_{cusp} seems perfectly consistent with Λ CDM.

5. Conclusion

It has been shown here that anomalies in the monochromatic (as opposed to differential) magnification ratios of cusp caustic lenses can all be explained naturally within the Λ CDM model with little if any substructure within the dark matter halo of the primary lenses. Extragalactic halos are enough to account for these anomalies. Furthermore, the typical observed anomalies in the monochromatic magnification ratios of several tenths of magnitudes – when compared to simple lens models – are easily explained in the same way. The contribution to flux anomalies from extragalactic halos is found to be significant. Measuring the amount of substructure that is within the primary lens halos for comparison with Nbody simulations will require a large number of lenses and an accurate prediction for the extragalactic contribution. These anomalies in the monochromatic

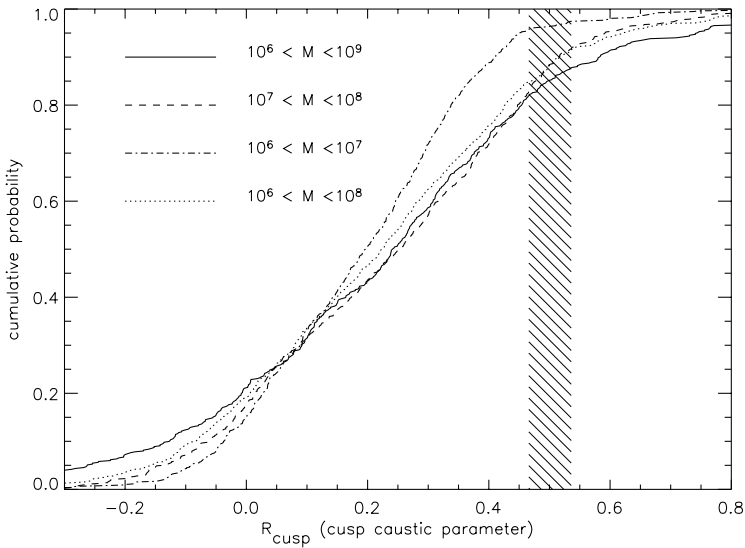


Figure 3. The cumulative distribution for R_{cusp} in the tight long axis case like B2045+265 with only extragalactic substructure. The observed value of R_{cusp} in the radio is shown by the hashed region. The included halo mass ranges are shown.

magnification ratios could also be explained by smaller scale structures since they do not provide significant constraints on the substructure mass.

It is significant that all of the observed cusp caustic parameters, R_{cusp} , are positive. In light of the marked asymmetry in the distributions of R_{cusp} from the simulations, the positive values can be seen as further support for the conclusion that these anomalies are being caused by some kind of small scale structure.

In contrast to the monochromatic magnification ratios, the spectroscopic gravitational lensing observations of Q2237+0305 require more small mass halos than are expected in the Λ CDM model. Bent multiply imaged radio jets also hint, although less securely, at a large number of small mass objects. The case for small mass substructure is not yet secure, but further data should resolve the issue. On the theoretical side, advances in cosmological simulations should soon make it possible to extend predictions for the mass function of substructures within the halos of large galaxies down to smaller masses and smaller galactocentric radii where they can be more directly compared with observations. At this time, there is an inconsistency that needs to be resolved between the Λ CDM model and the gravitational lensing observations.

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Discussion

C. KOCHANEK: I would like to point out that in the one case where we can actually see a substructure that substructure is in the lens.

B. METCALF: In that case the substructure is fairly large in comparison to the primary lens. You would expect a large substructure to be associated with the lens. At smaller masses the number density is higher and there are many more interlopers.

D. ALLOIN: To which extent would the source structure, not only the size, be a limiting factor in the approach?

B. METCALF: Yes, this could eventually be the biggest source of uncertainty. At this time we can say something about mass scales and number densities with just rough size scales. When there are many more lenses and we want to know more about the substructure this might become a limitation. One exception to this is that radio jets can have small hot spots that could be microlensed. This does not appear to be the case in Q2237+0305 since the radio and mid-IR flux ratios agree with each other.



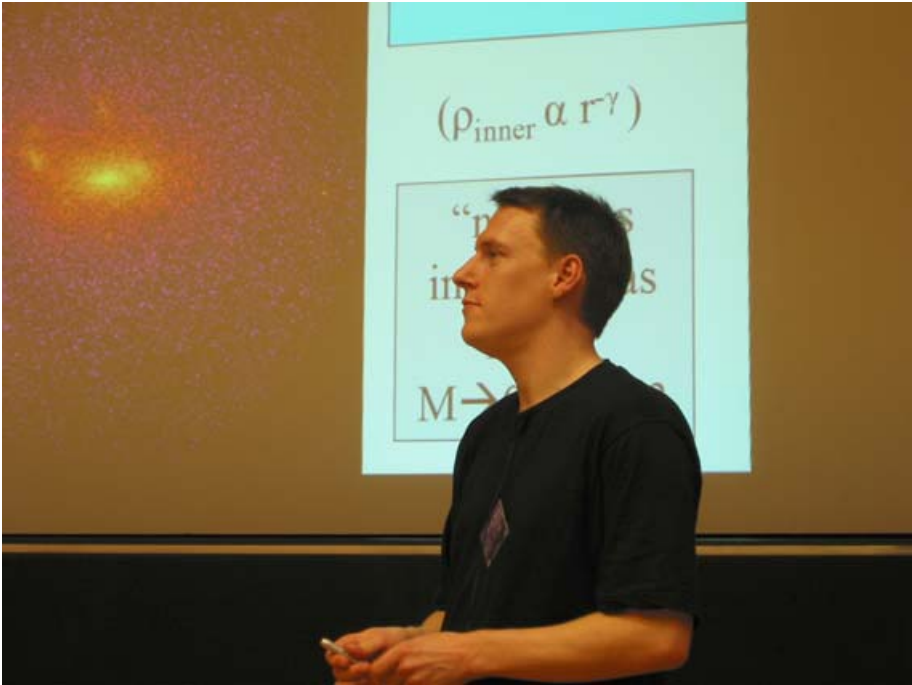
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