Flux Ratio Anomalies: Micro- and Milli-lensing

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Abstract. Simple models for lensing potentials that successfully produce the positions of quadruple images to high accuracy fail abysmally in reproducing the flux ratios of the multiple images, suggesting the presence of small scale structure within the lensing galaxies. It has been argued that the flux ratio anomalies observed at radio wavelengths signal the presence of CDM mini-halos. We argue that at least some of the anomalies observed at optical wavelengths result from micro-lensing by stars. This model succeeds in explaining observed asymmetry between minima and saddle-points of the light travel time only if a substantial fraction of the projected mass is in a smooth, dark component.

1. Flux Ratio Anomalies?

There is a theorem in gravitational lensing that says, under certain circumstances, a close pair of images in a quadruple system will be both bright and of equal brightness (e.g. Gaudi and Petters 2002). The archetype of such systems, PG1115+080 (Weymann et al. 1980), has a pair of bright images separated by 0′.48.

But as is often the case, the archetype turns out not to be archetypical. Zhao and Metcalf (2002) have examined a range of “reasonable” models for PG1115 and find that the rms magnitude difference for the A1 and A2 (figure 1) images ought to be roughly 10%. The observed difference appears to have varied with time, having ranged from 5-50% (Vanderriest et al. 1986; Kristian et al. 1993; Courbin et al. 1997; Iwamuro et al 2000), well outside the range allowed by the models. One might argue that the combination of intrinsic variability and gravitational time delay could produce the observed differences, but the predicted differential time delay between A1 and A2 is of order one day and the quasar varies much more slowly (Schechter et al. 1997).

Other quads with similar configurations have the same problem, only worse. MG0414+0534 has a I-filter magnitude difference $A1 - A2 = 0.9$ (Schechter and Moore 1993). By contrast the radio flux ratio (Moore and Hewitt 1977),

1The separation between images must be small compared to the displacement of the images from the galaxy and the gravitational potential must be smooth on the scale of the image separation. The theorem is then a direct consequence of expanding the light travel time as a power series in the neighborhood of a critical curve, keeping terms up to third order in distance from the critical curve.
A2/A1, is very nearly unity. Reimers et al. (2002) call HS0810+2554 a twin to PG1115, but its bright pair of images differ by 0.7 mag. Most recently and most dramatically, the system SDSS0924+0219 (Inada et al. 2003) has what appears to be a close pair of images with a flux ratio of nearly ten.

Such “flux ratio anomalies” are not restricted to systems with close pairs of images. Systems with three close images and a more distant image (e.g. B1422+231; Mao and Schneider 1998) and “Einstein crosses” (e.g. HE0435-1223; Wisotzki et al. 2002) exhibit similar anomalies.

2. Micro-lensing?

The problem with the theorem (and with the models) is that they assume a gravitational potential which is smooth on the scale of the image separation. With the discovery of the first lensed system Chang and Refsdal (1979) predicted flux variations due to micro-lensing by the stars in the intervening galaxy. The associated graininess in the gravitational potential will affect the fluxes if the Einstein rings of the stars are larger than the source.

Witt, Mao and Schechter (1995) attempted to explain the anomalous fluxes in MG0414 as the result of micro-lensing. They took the galaxy to be comprised entirely of stars (as opposed to an admixture of stars and dark matter) so as to maximize the effects of micro-lensing. The observed A2/A1 ratio was at the limits of what might reasonably be expected. But the flux ratio in Inada’s new system, SDSS0924, is more extreme than in MG0414, well outside the anything seen in the Witt et al. simulations.
Understandable though it might have been, Witt et al. were mistaken in thinking that a galaxy comprised entirely of stars would maximize micro-lensing fluctuations. Deguchi and Watson (1987) and Seitz, Schneider and Wambsganss (1994) had shown that for the case of zero shear, increasing the optical depth to micro-lensing beyond a certain point decreased the rms amplitude of the micro-lensing fluctuations. More recently, Schechter and Wambsganss (2002) have shown that for systems like MG0414, micro-lensing fluctuations are enhanced by keeping the surface mass density constant but substituting smooth (and presumably) dark matter for some (but not all) of the stellar micro-lenses. A case as extreme as that of SDSS0924 is no longer impossible.

This counterintuitive result may be explained by a two part argument. First, at high magnification, a screen of micro-lenses produces a large number of extra positive parity micro-images (Paczyński 1986; Wambsganss, Witt and Schneider 1993; Granot, Schechter and Wambsganss 2003). Negative parity micro-images can (and mostly do) have magnifications less than unity, but positive parity micro-images must have unit magnification or greater. As the number of positive parity micro-images grows large, the fluctuations drop as the square root of the number. On the other hand, at very low optical depth, fluctuations are rare and the rms must be small. One might reasonably expect the fluctuations to be largest when the number of extra positive parity micro-images is of order unity.

Paczyński (1986) has shown that for a random distribution of micro-lenses with convergence \( \kappa_* \), immersed in a smooth mass sheet with convergence \( \kappa_c \) and
Figure 3. Magnification probability distribution for a minimum (left) with \((\kappa_{\text{tot}}, \gamma) = (0.475, 0.425)\) and a saddle-point (right) with \((\kappa_{\text{tot}}, \gamma) = (0.525, 0.575)\), both with magnification \(\mu \approx 10\). The total convergence, \(\kappa_{\text{tot}}\), remains constant for each column. The smoothly distributed matter increases from top to bottom, with fractional contributions of 0\%, 75\%, 85\%, 95\% and 98\%, respectively. The three vertical lines indicate the following: short-dashed: \(\Delta m = 0\) mag (theoretically expected macro-magnification, \(\mu \approx 10\)); dotted: \(\langle \Delta m \rangle\) (average magnification in magnitudes); long-dashed: \(\mu_{\text{abs}} = 1.0\) (absolute magnification unity, i.e. unlensed case).
under the influence of an external shear $\gamma$, there is an equivalent configuration with no smooth component, but with effective convergence $\kappa_{\text{eff}}^* = \kappa_*/(1 - \kappa_c)$ and effective shear $\gamma_{\text{eff}}^* = \gamma/(1 - \kappa_c)$, subject to the condition that magnifications computed in the effective model, $\mu_{\text{eff}}^*$, must be multiplied by $(1 - \kappa_c)^{-2}$. By adjusting the relative contributions of $\kappa_*$ and $\kappa_c$ to the value of $\kappa_{\text{tot}}$ determined by the smooth lens model, one changes the number of extra positive parity micro-images.

Schechter and Wambsganss found (figure 3) that for values of $\kappa_{\text{tot}}$ and $\gamma$ typical of PG1115-like systems, a dark matter fraction of 50-90% of the surface density maximizes the micro-lensing fluctuations. They argue that such a dark matter fraction is consistent with the mass to light ratios observed for elliptical galaxies.

They also found that diluting a 100% grainy surface density with a smooth component affected positive and negative parity macro-images differently. In the case of positive parity macro-images (minima of the light travel time), substituting a smooth dark component introduces a lower limit on the combined flux of the micro-images, eventually narrowing the magnification distribution. By contrast negative parity macro-images (saddle-points of the light travel time) are quite vulnerable to demagnification by micro-lensing. A high magnification saddle-point is easily split into two low-magnification micro-saddles (Chang and Refsdal 1979; Schechter and Wambsganss 2002). The net result is that for pairs of bright macro-images in PG1115-like systems, the saddle-point is almost always fainter than the than the associated minimum.

In systems like PG1115, each image in the bright pair has a magnification of order 10. At the positions of the images, the shear $\gamma$ and the total convergence and shear $\kappa_{\text{tot}}$, are determined by the smooth lens model and are both roughly 0.5. But the relative contributions of stars, $\kappa_*$ and dark matter, $\kappa_c$ to the total convergence are unknown. Were the mass all in stars, the number of extra positive parity micro-images would be of order 3. If 80% of the convergence were in a smooth component, the effective magnification would be roughly 3 and the number of extra positive parity images would be of order unity.

In all of the above mentioned systems (save the case of HS0810, where the parities of the images are ambiguous) the saddle-points are fainter than predicted in the smooth models. The minimum/saddle-point asymmetry had been earlier noted in the theoretical work of Metcalf and Madau (2001), who saw differences in their cumulative magnification distributions for their saddle-points and minima, and in Witt et al. (1995) in their treatment of MG0414.

The foregoing considerations point to what would appear to a neat method for measuring the relative contributions of grainy and smooth matter to the surface mass density of lensing galaxies. One would assemble a “fair” sample of quadruple systems, model them using image positions (but not fluxes) as constraints, and adjust the ratio of grainy to smooth matter so as to match the observed distribution of flux residuals.

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2 A consequence of the requirement that there be at least one positive parity image, and that the minimum magnification for a positive parity image is $(1 - \kappa_c)^{-2}$.
3. Milli-lensing!

Astrophysics is cursed with a surfeit of explanations. In the present case there is second possible source of graininess. N-body simulations of the hierarchical clustering of cold dark matter produce large numbers of “mini-halos” within the halos of typical galaxies (Moore et al. 1999; Klypin et al. 1999). These can be reconciled with the much smaller numbers of dwarf satellites only if a mechanism is invoked to prevent the baryonic matter from forming stars in these mini-halos. But the mini-halos (which produce deflections of order a milliarcsecond) might still be expected to cause milli-lensing of background QSOs.

How then, might one distinguish between milli- and micro-lensing? Kochanek and Dalal (2003), following Koopmans and de Bruyn (2000), argue that quasar radio source sizes are expected to be larger than the Einstein rings of stars, ruling out micro-lensing as the source of radio flux ratio anomalies. The lensed system B1555+375 (Marlow et al. 1999) is a radio analog of PG1115, whose bright components have a flux ratio of 0.57. Kochanek and Dalal analyze a sample of radio quads and find that the brighter of the two saddle-points is significantly fainter than the model predictions.

Dalal and Kochanek (2002) argue that roughly 2% of the projected mass density (with a factor of three uncertainty) must be in the form of mini-halos. Evans and Witt (2002) argued that multipoles of higher order than quadrupole might produce similar results, but Kochanek and Dalal argue that these would require galaxies far more misshapen than the observed lenses.

4. Micro- and Milli-lensing!

While micro-lensing cannot explain the radio anomalies, milli-lensing can explain the optical anomalies. Is there the any need for micro-lensing?

Two separate lines of argument suggest that micro-lensing is also important. First, the broad emission line regions of quasars are thought to be larger than the Einstein rings of micro-lenses (e.g. Moustakas and Metcalf, 2002). An absence of broad emission line anomalies would argue for micro-lensing. Indeed differences between emission-line and continuum flux ratios in several systems (Wisotzki et al. 1993; Schechter et al. 1998; Burud et al. 2002). Second, micro-lensing produces uncorrelated variations in multiple images. These have been seen, most famously in Huchra’s lens, B2237+0305 (Woźniak et al. 2000) but also in HE1104-1805 (Schechter et al. 2003) and B0957+561 (Schild 1996; Refsdal et al. 2000), and with less coverage, in B1600+434 (Burud et al. 2001) and several other systems. The timescale for milli-lensing variations would be thousands of years. Thus it seems that both micro- and milli-lensing are at work.

How much of the discrepancy between the observed optical fluxes and the models is due to micro-lensing and how much is due to milli-lensing? Ideally one would observe lenses in both the radio and optical and compare flux ratios. The difference between the two would be attributable to micro-lensing. Unfortunately 90% of quasars are radio quiet. But with the advent of integral field units (and with judicious use of HST) one can imagine obtaining broad emission line flux ratios for a large sample of quads. We may therefore soon know whether micro- or milli-lensing is the major contributor to the observed
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problems. When we do we will have measures of the relative contributions of smooth and clumpy dark matter to the mass budget of galaxies.

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