

MICROLENSING IN Q2237+0305

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Q2237+0305 offers a unique opportunity to use spectrophotometric observations of microlensed high magnification events to examine the central engine of a quasar. The high quality of recent OGLE monitoring, in addition to the lengthening overall monitoring history for Q2237+0305 have allowed probabilities for the parameters of microlens mass, galactic transverse velocity and continuum source size to be determined. We discuss interpretations of features of the OGLE light-curves using the estimate for each parameter. The combination of optical and IR flux ratios provides a constraint on the extent of the mid-IR emission region.

1 Introduction

The QSO 2237+0305, sometimes known as Huchra's lens or the Einstein Cross (Huchra et al. 1985), is perhaps the most remarkable gravitational lens yet discovered. It comprises a foreground barred Sb galaxy ($z=0.0394$) whose nucleus is surrounded by four images of a radio-faint QSO ($z=1.695$). Broad band monitoring has shown that significant microlensing events occur. Since the optical depth to microlensing is of order unity at each of the image positions (eg. Kent & Falco 1988), the magnification effects on the source can be considered as a network of caustics moving across the source plane. Strong variation in a particular image results from the source either crossing a caustic or passing close to a cusp. Q2237+0305 is an ideal microlensing laboratory due to the relative closeness of the lensing galaxy and the nearly on-axis alignment. The time delay between the four quasar images is therefore less than a day, and the time-scale for events is typically 30-50 days. Analysis of light-curves for Q2237+0305 has yielded strong limits on the existence of low mass objects (eg. Wyithe, Webster & Turner 2000). In addition, analysis of caustic crossing events for Q2237+0305 hold the promise of a mapping of the intensity profile of the inner regions of the quasar central engine (eg. Agol & Krolic 1999).

Although Q2237+0305 has been monitored since its discovery, data collected by the OGLE collaboration over the last 3 years (Wozniak et al. (2000); see also <http://www.astro.princeton.edu/~ogle/ogle2/huchra.html>) has for the first time obtained data of sufficient coverage to clearly demonstrate smooth independent flux variation between the images. We provide interpretations for several features in the image A and C light-curves, and discuss their implications for future microlensing. The OGLE data adds to approximately 10 years of previously obtained, but less densely sampled photometry (eg. Corrigan et al. (1990) and Østensen et al. (1996)).

Table 1: Table of probabilities for model light-curve features corresponding to those in the 1999 image C event.

Event type	$P(\Delta t < 2wk)$	$P(\dot{M}_{mx} < 2)$	$P(M_{hgt} < .5)$	$P(\Delta M_{mn} < 0)$	$P(\Delta M_{mn} < 0)$
Cusp	0.11	0.83	0.55	0.50	0.95
+ve caustic	0.07	0.01	0.02	0.02	0.38
-ve caustic	0.05	0.04	0.13	0.98	0.99

2 Analysis of the OGLE Light-Curve

We apply simple statistics describing event heights and light-curve derivatives a posteriori to specific features in the published light-curves. We use the results to interpret features found in monitoring data. In particular we discuss whether the large scale variation in image C (1999) was due to the source having crossed a caustic or moved outside of a cusp.

2.1 Statistics of the 1999 light-curve peak in image C

The image C light-curve shows a remarkable resolved peak described by ~ 35 points on separate days spanning ~ 7 months. By December 1999 the image C light-curve had dropped to a level similar to the end of the 1998 observing season. The peak is quite symmetric having reached a height $M_{hgt} \sim 0.5$ magnitudes above the 1998 level. The maximum derivative reached both before and after the event peak was $\dot{M}_{mx} \sim 2$ mags/year. Images B and D remained fairly constant during this period suggesting constant intrinsic luminosity. The event properties are discussed in relation to model calculations of the probability for their values for cusp events, and caustic crossings with appearing (+ve) and disappearing (-ve) critical images. The results are summarised in Tab. 1.

We find that a \dot{M}_{mx} of ~ 2 magnitudes per year is inconsistent at $> 99\%$ level with the event having been a +ve caustic crossing. In addition, we find that a -ve caustic crossing is excluded at the 95% level. A cusp cannot be excluded on the basis of the maximum derivative (though it is higher than expected). If the light-curve minimum preceding the 1999 image C event is assumed to have been at the level of the 1998 season then the height of the peak maximum above the previous local minimum is $M_{hgt} \sim 0.5$ magnitudes. $\Delta M_{hgt} \sim 0.5$ magnitudes is typical if the event is due to a cusp, and is ruled out at the 98% level if the event is +ve caustic crossing. If the event is a -ve caustic crossing the results are inconclusive.

Wyithe, Webster, Turner & Agol 2000 describes a general function to determine how long one should wait (Δt_e) for a HME following a hypothetical observed light-curve derivative. On the 19th of June 1999 monitoring showed image C rising at a rate of 1.21-1.78 mags/year. The light-curve peaked on ~ 1 July, about 2-weeks after the aforementioned derivative. This is surprisingly early for all types of events. At the 90% – 95% level, caustic crossing events are excluded.

Constraints on the event type of the OGLE image C HME are placed by both the maximum derivative observed prior to the event peak, and the height of the peak above the previous minima. +ve caustic crossings are excluded by both these measurements (even when potential systematic errors in source size are assumed). In addition, -ve caustic crossings are excluded by the measured maximum derivative. The cusp interpretation is consistent with both measurements. Based on the above evidence we therefore conclude that the event observed for image C was probably a cusp event rather than a caustic crossing.

At the time of writing the image C light-curve was still in decline, but appeared to be decelerating (+ve second derivative). If the light-curve flattens out at a level approximately equal to that of the 1998 season ($\Delta M_{mn} \sim 0$), then the -ve caustic crossing interpretation will

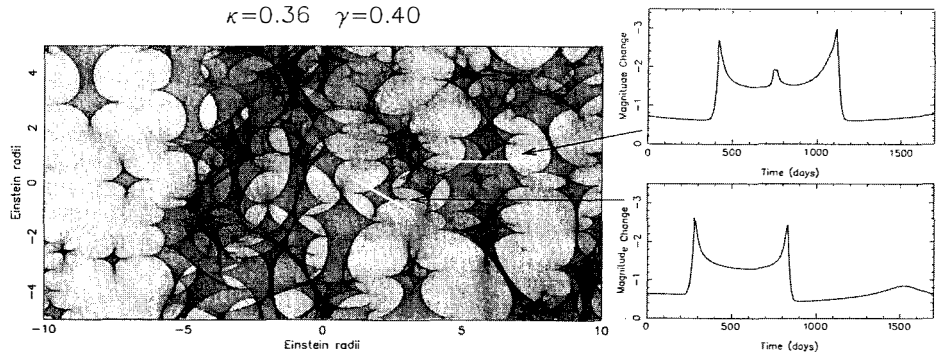


Figure 1: Examples of double-horned profile (top right) and double horned profile with an additional cusp event (lower right). Corresponding source tracks are overlaid on a magnification pattern.

be ruled out at the 95% level. Assuming that the previous light-curve minimum occurred during 1998, the $+ve$ caustic crossing interpretation is already ruled out at $> 95\%$.

Monitoring shows a $\Delta M_{mn} \sim 0.8$ magnitude rise between the 1997 image C minimum and the 1998 level, suggesting an event in between those observing seasons. We assume that the intrinsic source luminosity was approximately constant over this period, which is supported both by the facts that image A changed by < 0.2 magnitudes and that the other images show opposite trends. We find that ΔM_{mn} is consistent with a $+ve$ caustic crossing having occurred between the 1997 and 1998 observing seasons, but rules out $-ve$ caustic crossings ($\sim 99\%$) and cusp events ($\sim 95\%$). We therefore infer that a $+ve$ caustic crossing was missed between the 1997 and 1998 observing seasons.

2.2 The next image C HME

Now we assume that there was a $+ve$ caustic crossing between the 1997 and 1998 observing seasons, and investigate when we should next see a caustic crossing in image C. Due to the typical diamond formation of fold caustics, the case of a $+ve$ followed by a $-ve$ caustic crossing is common. Similarly, inspection of model light-curves shows that cusp events follow $-ve$ caustic crossings as the source moves past the cusp associated with that caustic (this feature is seen in the double horned profile that is characteristic of the Chang-Refsdal lens). However we have inferred that the OGLE image C light-curve shows a $+ve$ caustic crossing followed by a cusp event. Such a combination is much less common and is due to the source moving past a cusp formed from two fold caustics other than the one responsible for the $+ve$ caustic crossing HME. However, it too can be found in model light-curves. Examples of the two scenarios are shown in Fig. 1. One way of analysing the separation between the cusp event peak and the next caustic crossing is to calculate the ratio of the time between the cusp event peak and last caustic crossing and the time between the cusp event peak and next caustic crossing. The typical ratio is 1 and we expect it to be between $\sim \frac{1}{4}$ and ~ 4 , yielding a most likely arrival time for the next event of ~ 500 days, and an upper limit of ~ 2000 days ($\sim 90\%$).

2.3 The next image A HME

The OGLE data also shows image A brightening over the 1999 season, with the most rapid variations occurring in the latter observations. On the 30th of October 1999 monitoring showed

a rise in image A, of 1.41-1.88 mags/year (we used observations on the 20th of October, 30th of October and 9th of November). Having observed a derivative in the quoted range means that a *+ve* caustic crossing is very unlikely, and a *-ve* caustic crossing is the most likely option. Unfortunately, these results predict that an event will occur in image A between the 1999 and 2000 observing seasons. If the impending event is assumed to be a *-ve* caustic crossing, with a previous minimum occurring during the 1998 season, then we predict that the image A light-curve should have a subsequent minimum at a level $\sim 1 - 1.5$ magnitudes fainter than the November 1999 level.

2.4 Combining IR and Optical observations

Observations in September 1999 show an image B:A I-band flux ratio of ~ 0.3 . However, at the same epoch, mid-IR observations (Agol et al. 2000) yield an image B:A K-band flux ratio of $\sim 1.1 \pm 0.1$. This dramatic colour difference between images A and B is interpreted as being due to microlensing of the optical continuum emission region (which is smaller than the microlens Einstein radius), while the larger IR emission region more closely reflects the true magnification ratio. Modelling shows that given the optical flux ratio, the IR emitting region should be $\sim 100 - 1000$ times larger than the I-band emission region to produce the observed K-band flux ratio. This indicates that the infrared emission is produced by hot dust rather than non-thermal synchrotron emission (Agol et al. 2000).

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