

*Letter to the Editor***Caustic crossings in quasar light curves?****M.R.S. Hawkins**

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Received 5 August 1998 / Accepted 21 October 1998

**Abstract.** Numerical simulations and theoretical studies of the gravitational microlensing effect of a population of small bodies distributed along the line of sight to a compact light source such as a quasar indicate that caustic crossing effects will be present given a sufficiently large optical depth to lensing. These events will produce characteristic patterns in the quasar light curve. In this paper we use a large sample of quasar light curves to search for features with the properties of caustic crossing events. Two good candidates are presented which it is argued are not easily explained as intrinsic variation of the quasars. The relation between these events and microlensing features seen in multiple quasar systems are discussed, as well as the implications for the dark matter problem of a population of microlensing bodies.

**Key words:** galaxies: quasars: general – dark matter – gravitational lensing

**1. Introduction**

Over the past 10 years or so several groups have published numerical simulations of the gravitational microlensing effect of a distribution of compact bodies along the line of sight to a distant light source such as a quasar. These light curves contain a number of identifiable features which depend on the optical depth to lensing, the size and structure of the source and the mass and velocity of the lenses. In particular, lenses can combine non-linearly to produce caustics which result in characteristic high-amplification events. In this paper we make the case that such features may actually be seen in observed quasar light curves, and present examples from a large scale monitoring programme which have all the properties of caustic crossing events. This implies the existence of a large population of microlensing bodies with masses which can be estimated from the duration of the caustic crossings to be subsolar.

The first numerical simulations of microlensing (Paczynski 1986) show undulating variation, punctuated by double spiked structures produced by caustic crossings. Since then a number of more sophisticated simulations have been carried out (Kayser et al. 1986, Schneider & Weiss 1987, Lewis et al. 1993), as well as studies of the effect of microlensing on extended sources (Refsdal & Stabell 1991). The question of whether microlens-

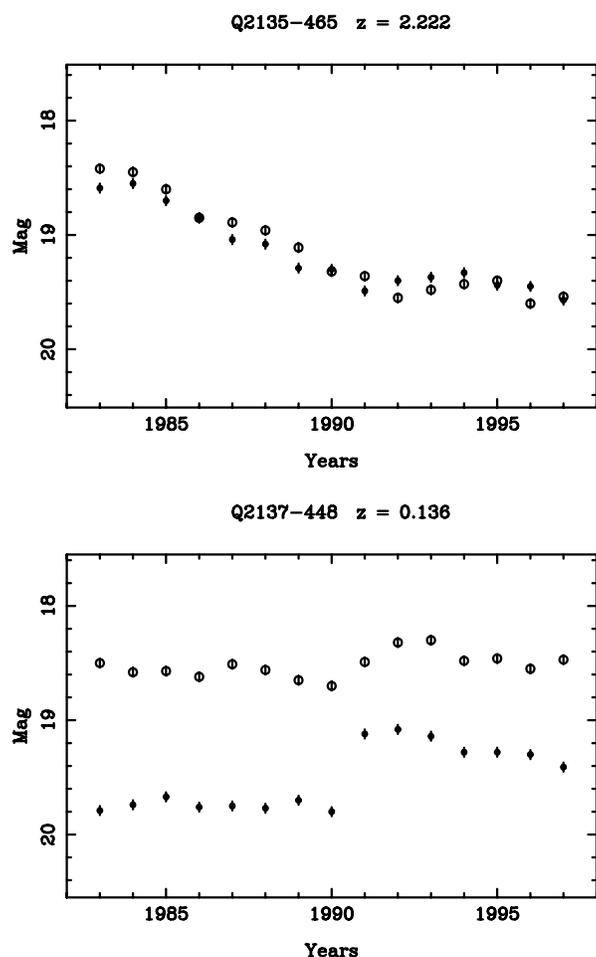
ing is actually seen in quasar light curves has also been investigated (Schneider & Weiss 1987), and it seems clear that, at least in the case of multiply lensed quasars, microlensing is taking place (Schild 1996, Irwin et al. 1989, Corrigan et al. 1991). The possibility that all quasars at sufficiently high redshift are being microlensed, and that this accounts for most of the observed variation, has been argued in a number of papers (Hawkins 1993, 1996, Hawkins & Taylor 1997) on the basis of statistical analysis of the quasar light curves. The relevance of most numerical simulations to observations of quasar light curves depends on the optical depth for microlensing of any population of lenses. If they have an optical depth around unity as they will in multiply lensed systems then complicated caustic patterns can be expected, and this will also be the case for a cosmological critical density of lenses. However the nature of the variation is different for low optical depth where individual events can be distinguished, as illustrated by Schneider (1993).

Statistical tests are inevitably blunt weapons, and there is much to be learned from examining the structure of individual light curves with a view to identifying features which can unambiguously be attributed to microlensing. In this paper light curves for a large sample of isolated quasars are examined for the characteristic features of caustic crossings produced by a large optical depth of microlenses. Two good candidates are presented, and discussed on the basis of current quasar models.

**2. Data analysis**

The parent sample of quasar light curves which was used for the investigation has already been described in detail (Hawkins 1996, Hawkins & Véron 1995), although it has been updated by the addition of five more yearly epochs. It is based on COSMOS and SuperCOSMOS measures of a large set of plates taken with the UK Schmidt telescope in ESO/SERC Field 287 centered on 21h 38m,  $-45^\circ$  (1950). The dataset contains homogeneous yearly coverage from 1983 to 1997 in two colours, a blue passband (IIIa-J/GG395) and a red passband (IIIa-F/RG630).

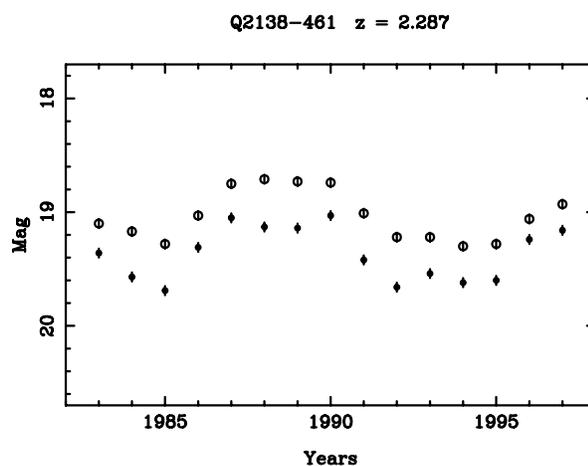
The idea of the project was to identify caustic crossing events in the set of light curves. The possibility of implementing an algorithm for automatically detecting the characteristic twin spiked shape was reluctantly rejected due to the difficulty of defining a sufficiently general template. The search was thus



**Fig. 1.** Light curves for two quasars. Filled and open circles are blue and red passband measures respectively. Error bars are based on measured photometric errors.

carried out by eye, which although exceptionally well suited to detecting patterns, results in an inevitable loss of statistical objectivity.

The first impression on scanning through large numbers of light curves in two colours is that the variation is on the whole close to being achromatic, and this can be supported by a statistical test (Hawkins 1996). A good example of such a light curve is shown in the top panel of Fig. 1 where no systematic colour change occurs over a change in brightness of 1.2 magnitudes. More careful examination however shows small departures from achromaticity for many of the light curves, and in a few cases very large differences. The bottom panel shows the light curve for a low luminosity low redshift quasar undergoing a small outburst. This feature is most unlikely to be caused by microlensing due to the low redshift of the quasar, but is very much what one would expect from an intrinsic event. The idea would be that an outburst in the hot blue core of an accretion disk would propagate outwards becoming smoothed out and degraded by the time it reached the cool red outer part of the disk. If there is a time lag between the two colours for the onset of the event it is clearly less than a year.



**Fig. 2.** Light curve for a quasar showing a possible caustic crossing. Symbols as for Fig. 1

Fig. 2 shows an event which appears to have the characteristics of a caustic crossing. The morphology of such events is well illustrated by the various groups which have carried out numerical simulations of microlensing (Kayser et al. 1986, Schneider & Weiss 1987, Lewis et al. 1993). The double spiked features are readily spotted in the set of light curves, but more often than not are overlaid by short term events which distort the morphology. The light curve in Fig. 2 is a particularly clean example. The variation is characterised by a rise in the blue to a double cusp shaped feature followed by a fall. The cusps are smoothed out in the red light curve which is symmetrically situated over the blue, with a smaller amplitude. The explanation for this in the context of microlensing would be that a compact blue core is strongly amplified by a lens with significantly larger Einstein radius during a caustic crossing. The red light curve however is dominated by the outer parts of the accretion disk, which is of comparable size to the Einstein radii of the lenses, and is amplified less strongly with no discernible cusps. This chromatic type of behaviour has been discussed from a theoretical point of view by Wambsganss & Paczyński (1991). It seems possible that one could contrive an explanation for this light curve based on intrinsic variation, but the symmetry of the configuration is hard to account for. Also, the cusp like features which are so much a feature of microlensing have no natural explanation as intrinsic events.

Although the light curve in Fig. 2 is suggestive of a microlensing event, the rather small amplitude leaves open the possibility that it consists of a juxtaposition of small intrinsic events. To circumvent this difficulty a detailed search was carried out on the largest amplitude quasars ( $\delta m > 1.5$ ) to look for features with the characteristics of caustic crossings. Of the 10 quasars with complete light curves in  $B_J$  and  $R$ , the two best candidates are shown in Fig. 3. In each case the blue flux rises and falls sharply, within the space of about a year. The red flux on the other hand actually starts to increase two years or so before the blue, and appears to continue to fall after the blue has bottomed out. It does however only achieve a much smaller amplitude. This is very hard to understand in the context of in-

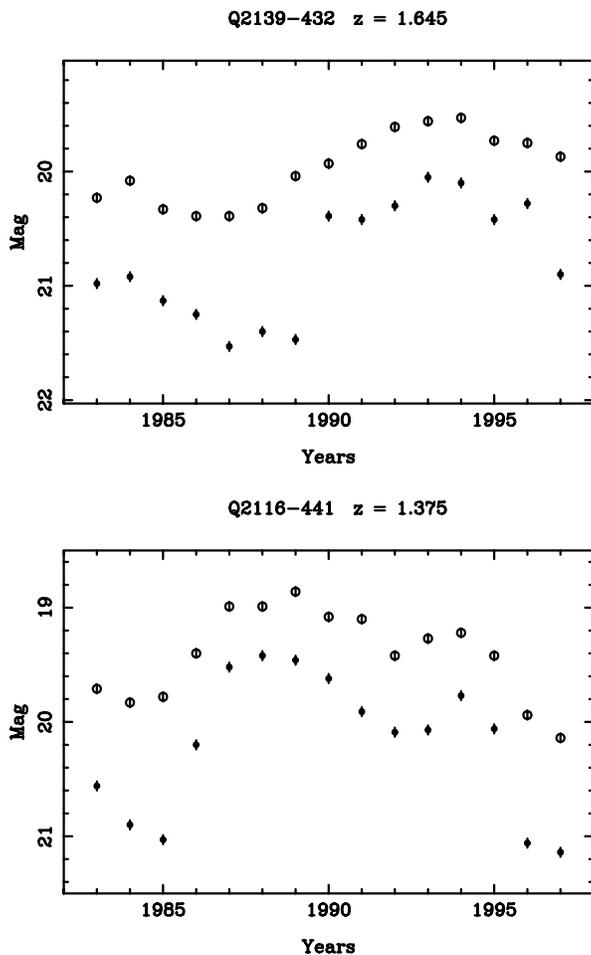


Fig. 3. Light curves for two quasars showing all the characteristics expected of caustic crossing events. Symbols as for Fig. 1.

intrinsic variation, but as before is in accord with the microlensing model. In this case, the larger size of the accretion disk in the red produces early amplification of the source, but this same large size results in a smaller total amplitude than in the blue.

### 3. Discussion and conclusions

The availability of light curves for the components of multiply lensed quasars can in principle provide unambiguous templates for intrinsic variation and microlensing. The best data available at present is for the double quasar Q0957+561. Intensive CCD monitoring by two groups (Schild & Thomson 1997, Kundić et al. 1997) from 1993 to 1996 show small fluctuations of around 0.15 magnitudes which are very well matched in both images after allowing for the time delay. These must be intrinsic variations and appear to be similar in character, although of a smaller amplitude, to those seen in the Seyfert galaxy NGC 5548 by Clavel et al. (1991). This similarity extends to chromatic effects. Kundić et al. (1997) show that when Q0957+561 gets intrinsically brighter it becomes bluer, as seen in NGC 5548. It is only when monitored over much longer timescales that convinc-

ing microlensing effects become apparent (Schild & Thomson 1993). When the light curves of the two components are subtracted after applying the time delay, the dominant feature is a long term decrease in the magnitude difference of about 0.3 magnitudes over a period of 12 years. Effects of this sort are seen in the Field 287 quasar sample, but do not appear to be associated with a caustic crossing.

The time interval between the peaks provides a very rough way of estimating the mass of the microlensing bodies. In simple two mass systems the separation of the caustics is typically a few tenths of an Einstein radius (Schneider & Weiss 1986). For more complex arrangements of lenses the separations can be larger, up to a few Einstein radii (Lewis et al. 1993). The light curves in Figs. 2 and 3 have separations of around four years between the caustics, and if we adopt a typical lens velocity across the line of sight of  $600 \text{ km. sec}^{-1}$ , the distance travelled is around  $2 \times 10^{-3} \text{ pc}$ . This implies (Hawkins 1996) a lens mass of  $10^{-2} M_{\odot}$ , a factor of ten larger than that derived from a statistical treatment of the light curves (Hawkins 1996). The uncertainties in this calculation are rather large, at least an order of magnitude, but if this difference is real it is probably due to the fact that it is the most massive lenses which are likely to give the most pronounced caustic patterns.

The relative ease with which events resembling caustic crossings can be found in the set of light curves strongly suggests that they could be a fundamental aspect of the variation mechanism. It is clearly not possible to rule out any conceivable intrinsic mechanism which can produce the observed features, but until such a mechanism is proposed it seems a viable alternative to attribute them to microlensing. This then adds to the existing case for a population of planetary mass bodies sufficient to account for the dark matter. Other lines of argument include the statistical analysis of quasar light curves (Hawkins 1996), microlensing in gravitationally lensed multiple quasar systems (Schild 1996, Hawkins 1997) and the recent detection of a Jupiter mass body by the MACHO team (Bennett et al. 1997, Hawkins 1998). Although none of these strands of evidence is conclusive in itself, the case for dark matter in the form of planetary mass compact bodies is becoming steadily more broadly based.

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