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Microlensing of Quasars

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Abstract: Microlens-induced variability in multiple quasars can be used to study two cosmological issues of great interest, the size and brightness profile of quasars on one hand, and the distribution of compact (dark) matter along the line of sight on the other. Here a summary is given of recent theoretical progress as well as observational evidence for quasar microlensing, plus a discussion of desired observations and required theoretical studies.

Keywords: gravitational lensing — dark matter — quasars: general

1 Introduction

The lensing effects on quasars by compact objects in the mass range $10^{-6} \leq m/\mathrm{M}_\odot \leq 10^6$ is usually called 'quasar microlensing'. The microlenses can be ordinary stars, brown dwarfs, planets, black holes, molecular clouds, globular clusters or other compact mass concentrations. The relevant length scale for microlensing (in the quasar plane) is the Einstein radius of the lens:

$$r_E = \sqrt{\frac{4GM}{c^2}\frac{D_S D_{LS}}{D_L}} \approx 4 \times 10^{16}\sqrt{M/\mathrm{M}_\odot}\,\mathrm{cm},$$

where 'typical' lens and source redshifts of $z_L \approx 0.5, z_S \approx 2.0$ are assumed for the expression on the right hand side (G, c and D_L, D_S, D_{LS} have their usual meaning). Quasar microlensing turns out to be an interesting phenomenon, because the size of the continuum emitting region of quasars is comparable to or smaller than the Einstein radius of stellar mass objects. The angular Einstein radius is $\theta_E = r_E/D_S \approx 10^{-6}\sqrt{M/\mathrm{M}_\odot}$ arcsec, by far too small for direct observations. What makes microlensing observable anyway is the fact that observer, lens(es) and source move relative to each other. Due to this relative motion, the micro-image configuration changes with time, and so does the total magnification, i.e. the sum of the magnifications of all the micro-images. And this change in magnification over time can be measured: microlensing is a 'dynamical' phenomenon. The standard lensing time scale t_E is the time it takes the source to cross the Einstein radius of the lens, i.e. $t_E = r_E/v_\perp \approx 15\sqrt{M/\mathrm{M}_\odot}v_{600}^{-1}$ years, assuming a relative transverse velocity of $600\,\mathrm{km\,s^{-1}}$. However, in practice we can expect fluctuations on much shorter time intervals: if a source crosses one of the sharp caustic lines that separate regions of low and high magnification, we can observe a large change in magnification during the time t_{cross} it takes the source to cross its own radius $R_{\mathrm{source}} : t_{\mathrm{cross}} = R_{\mathrm{source}}/v_\perp \approx 4R_{15}v_{600}^{-1}$ months. Here the quasar size R_{15} is parameterised in units of 10^{15} cm.

2 Theoretical Work on Quasar Microlensing

Right after the discovery of the first multiply imaged quasar, Chang & Refsdal (1979) suggested that the flux of the two quasar images can be affected by stars close to the line of sight. Gott (1981) suggested that a heavy halo made of low mass stars 'should produce fluctuations of order unity in the intensities of the QSO images on time scales of 1–14 years.' Young (1981), Paczyński (1986), Kayser, Refsdal & Stabell (1986) and Schneider & Weiss (1987) used different techniques to explore microlensing light curves and magnification distributions. The first observational evidence for quasar microlensing in the quadruple quasar Q2237+0305 was presented by Irwin et al. (1989). Such fluctuations could be explained by the lensing action of ordinary stars and be used to put a limit on the quasar size (Wambsganss, Paczyński & Schneider 1990). Later, Witt (1993) and Lewis et al. (1993) developed a new technique for the investigation of microlensing. More recently, Lewis et al. (1998) showed that spectroscopic monitoring of multiple quasars can be used to probe the broad line regions. Fluke & Webster (1999) explored analytically caustic crossing events for a quasar. Wyithe, Webster & Turner (2000a) and Wyithe et al. (2000b) explored and found limits on the quasar size and on the mass function in Q2237+0305. In the last two years new techniques to recover the one-dimensional brightness profile of a quasar were developed, based on earlier work by Grieger, Kayser & Refsdal (1988) and Grieger, Kayser & Schramm (1991). Agol & Krolik (1999) showed that by frequent monitoring of a caustic crossing event in many wave bands (they assumed of order 40 data points in eleven filters over the whole electromagnetic range), one can recover a map of the frequency-dependent brightness distribution of a quasar. Yonehara et al. (1998) in a similar approach explored the effect of microlensing on various accretion disk models.

The early papers on microlensing made four predictions concerning the scientific success. With microlensing

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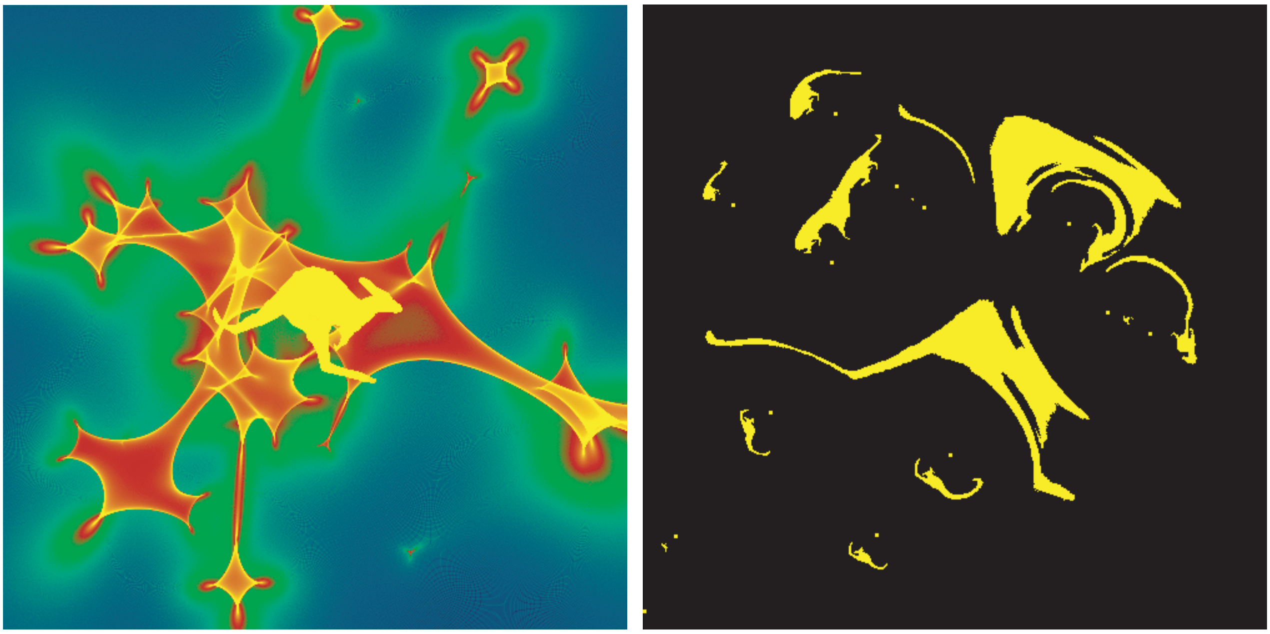

Figure 1 Illustration of how a caustic/magnification distribution (left) of stars/compact objects can distort and differentially magnify a background object (right).

we should be able to 1) determine the effects of compact objects between the observer and the source, 2) determine the size of quasars, 3) determine the two-dimensional brightness profile of quasars, 4) determine mass (and mass distribution) of lensing objects. At this moment, it can be stated that 1) has been achieved. Some limits on the size of quasars have been obtained, so 2) is partly fulfilled. We are still (far) away from solving promise 3), and concerning point 4) it is fair to say that it was shown that the results are consistent with certain mass ranges.

3 Observational Evidence for Quasar Microlensing

The Einstein Cross: Quadruple Quasar Q2237+0305

Since the first evidence for microlensing by Irwin et al. (1989) in this system, Q2237+0305 has been monitored by many groups (Corrigan et al. 1991; Østensen et al. 1996; Lewis et al. 1998). The most recent (and most exciting) results (Woźniak et al. 2000) show that all four images vary dramatically, going up and down like a rollercoaster in the last three years: $\Delta m_A \approx 0.6$ mag, $\Delta m_B \approx 0.4$ mag, $\Delta m_C \approx 1.3$ mag, $\Delta m_D \approx 0.6$ mag.

The Double Quasar Q0957+561

The microlensing results for the double quasar Q0957+561 are not quite as exciting. In the first few years, there appears to be an almost linear change in the (time-shifted) brightness ratio between the two images ($\Delta m_{AB} \approx 0.25$ mag over 5 years). But since about 1991, this ratio stayed more or less 'constant' within about 0.05 mag, so not much microlensing was going on in this system recently (Schild 1996; Pelt et al. 1998; Schmidt & Wambsganss 1998). At this moment, the possibility for some small amplitude rapid microlensing (cf. Colley & Schild 2000) cannot be excluded; however, one needs a very well determined time delay and very accurate photometry, in order to establish that. With numerical simulations and limits obtained from three years of Apache Point monitoring data of Q0957+561, and based on the Schmidt & Wambsganss (1998) analysis, we extend the limits on the masses of 'machos' in the (halo of the) lensing galaxy: the small 'difference' between the time-shifted and magnitude-corrected lightcurves of images A and B excludes a halo of the lensing galaxy made of compact objects with masses of up to $10^{-2} M_\odot$ (Wambsganss et al. 2000), see Figure 2.

Other multiple quasars/radio microlensing?

A number of other multiple quasar systems are being monitored more or less regularly. For some of them microlensing has been suggested (e.g. H1413+117, Østensen et al. 1997; or B0218+357, Jackson, Xanthopoulos & Browne 2000). In particular the possibility for 'radio'-microlensing appears very interesting (B1600+434, Koopmans & de Bruyn 2000; also Koopmans, these proceedings), because this is unexpected, due to the presumably larger source size of the radio emission region. The possibility of relativistic motion of radio jets may make up for this 'disadvantage'.

4 Unconventional Considerations on Quasar Microlensing

Microlensing in individual quasars?

There were a number of papers interpreting the variability of individual quasars as microlensing (e.g., Hawkins & Taylor 1997; Hawkins 1998). Although this is an exciting possibility and it could help us detect a population of cosmologically distributed lenses, it is not entirely clear at this point whether the observed fluctuations can be really

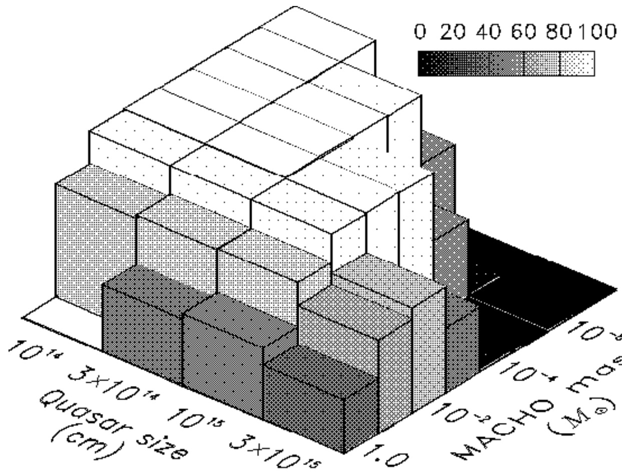

Figure 2 This ‘exclusion diagram’ visualises which part of the parameter space ‘quasar size’–‘microlens mass’ can be excluded with what probability (indicated by height and colour of the columns/bars; e.g., the white bar for a size of 10^{15} cm and a mass of $10^{-2} M_\odot$ means this parameter pair is excluded with 100% probability; light grey bars for $10^{-1} M_\odot$ reflect about 80% exclusion probability). This analysis is based on a comparison between monitoring data of Q0957+561A, B and intensive numerical simulations (for more details see Wambsganss et al. 2000).

attributed to microlensing. After all, quasars are intrinsically variable (otherwise we could not measure time delays), and the expected microlensing in single quasars must be smaller than in multiply imaged ones, due to the lower surface mass density. More studies are necessary to clarify this issue.

‘Astrometric microlensing’: centroid shifts

An interesting aspect of microlensing was explored by Lewis & Ibata (1998). They looked at centroid shifts of quasar images due to microlensing. At each caustic crossing, a new very bright image pair emerges or disappears, giving rise to sudden changes in the ‘center of light’ positions. The amplitude could be of order 100 microarcseconds or larger, which should be observable with the next generation of astrometric satellites, like SIM (Space Interferometry Mission), to be launched in June 2006.

Microlensing: here and there!?

In most cases of quasar microlensing, the surface mass density (or optical depth) is of order unity. In contrast to that, the ‘local group’ microlensing (Alcock et al. 2000; Aubourg & Palanque-Delabrouille 1999; Udalski et al. 2000) deals with low optical depths, where the action is due to single lenses or physical binaries. Since there are interesting similarities (search for dark matter, i.e. machos — massive compact halo objects) as well differences between these two regimes of microlensing, in Table 1 a few quantities relevant to the two types of microlensing are compared to each other.

5 Quasar Microlensing: Now and Forever?

Monitoring observations of various multiple quasar systems in the last decade have clearly established that the phenomenon of microlensing exists. There are uncorrelated variations with amplitudes of more than a magnitude and time scales of weeks to years. However, in order to get to a really quantitative understanding, much better monitoring programs need to be performed.

On the theoretical side, there are two important questions: what do the lightcurves tell us about the lensing objects, and what can we learn from them about the size and structure of the quasar. As response to the first question, the numerical simulations are able to give a qualitative understanding of the measured light curves (detections and non-detections), in general consistent with ‘conservative’ assumptions about the object masses and velocities. But due to the large number of parameters (quasar size, masses of lensing objects, transverse velocity) and due to the large variety of light curve shapes, no satisfactory quantitative explanation or even prediction could be achieved. So far mostly ‘limits’ on certain parameters have been obtained. The prospects of getting much better light curves of multiple quasars, as shown by the OGLE collaboration, should be motivation enough to explore this quantitative direction in much more detail.

The question of the quasar structure deserves much more attention. Here gravitational lensing is able to explore an astrophysical field that is unattainable by most other means. Hence much more effort should be put into attacking this problem. This involves much more ambitious observing programs, with the goal to monitor caustic crossing events in many filters over the whole electromagnetic spectrum, and to further develop numerical techniques to measure the quasar size and the (one-dimensional) profile from unevenly sampled data in (not enough) different filters.

In relation to the ‘early promises’ mentioned above, the future goals for quasar microlensing can be summarised

Table 1. A few properties for the two regimes of microlensing in search of 'machos' are compared to each other: local group microlensing and quasar microlensing. (The last three lines are very rough estimates.)

Lensing galaxy:	Milky Way	Lens in Q0957+561
Distance to Macho known?	no	yes
Velocity of Macho known?	no	(no)
Mass?	???	???
Optical depth?	$\approx 10^{-7}$	≈ 1
Einstein angle ($1\,M_\odot$)?	$\approx$1 milliarcsec	$\approx$1 microarcsec
Time scale?	hours to years	weeks to decades
Event?	individual/simple	coherent/complicated
Default light curve?	smooth	sharp caustic crossing
When/who proposed?	Paczyński 1986	Gott 1981
First detection?	EROS/MACHO/OGLE 1993	Schild 1996 (Irwin et al. 1989)
No. people involved	$\sim$100	$\sim$20
Telescope hours	$\sim$40 000	$\sim$1000
CPU years	$\sim$500	$\sim$10

as follows: 1) detect microlensing unambiguously in MORE gravitationally lensed systems; 2) yes, determine the size of the continuum emitting regions of quasars; 3) microlensing is one of the very few tools that make it possible to determine the two-dimensional brightness profile of quasars: go for it! 4) determining masses and mass functions of compact (dark?) objects can make you famous and enrich the community. Applying the strategy of the groups involved in 'local microlensing', and considering the potential of what we can learn about the lensed as well as the lensing objects, it is high time for better planned, organised and coordinated observing campaigns or even a dedicated telescope for quasar microlensing.

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