Cosmological Microlensing

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Abstract.

Variability in gravitationally lensed quasars can be due to intrinsic fluctuations of the quasar or due to “microlensing” by compact objects along the line of sight. If disentangled from each other, microlens-induced variability 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. In particular, multi-waveband observations are useful for this goal.

In this review recent theoretical progress as well as observational evidence for quasar microlensing over the last few years will be summarized. Comparison with numerical simulations will show “where we stand”. Particular emphasis will be given to the questions microlensing can address regarding the search for dark matter, both in the halos of lensing galaxies and in a cosmologically distributed form. A discussion of desired observations and required theoretical studies will be given as a conclusion/outlook.

1. What is cosmological microlensing?

1.1. Mass, length and time scales

The lensing effects of cosmologically distant compact objects in the mass range

\[ 10^{-6} \leq m/M_\odot \leq 10^6 \]

on background objects is usually called “cosmological microlensing”. The “source” is typically a background quasar, but in principle other distant source can be microlensed as well, i.e. distant supernovae or gamma-ray bursters. The only “condition” is that the source size is comparable to or smaller than the Einstein radius of the respective lenses.

The microlenses can be ordinary stars, brown dwarfs, planets, black holes, molecular clouds, or other compact mass concentrations (as long as their physical size is smaller than the Einstein radius). In most practical cases, the micro-lenses are part of a galaxy which acts as the main (macro-) lens. However, microlenses could also be located in, say, clusters of galaxies or they could even be imagined “free floating” and filling intergalactic space.
The relevant length scale for microlensing is the Einstein radius of the lens:

\[ r_E = \sqrt{\frac{4GM_DSD_{LS}}{c^2D_L}} \approx 4 \times 10^{16} \sqrt{\frac{M}{M_\odot}} \text{ cm}, \]

where “typical” lens and source redshifts of \( z_L \approx 0.5 \) and \( z_S \approx 2.0 \) were assumed for the expression on the right hand side (\( G \) and \( c \) are the gravitational constant and the velocity of light, respectively; \( M \) is the mass of the lens, \( D_L, D_S, \) and \( D_{LS} \) are the angular diameter distances between observer – lens, observer – source, and lens – source, respectively).

This length scale translates into an angular scale of

\[ \theta_E = \frac{r_E}{D_S} \approx 10^{-6} \sqrt{\frac{M}{M_\odot}} \text{ arcsec}. \]

It is obvious that the image splittings on these angular scales can not be observed directly. What makes microlensing observable any way 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.

There are two time scales involved: the standard lensing time scale \( t_E \) is the time it takes the source to cross the Einstein radius of the lens, i.e.

\[ t_E = \frac{r_E}{v_\perp} \approx 15 \sqrt{\frac{M}{M_\odot}} v_600^{-1} \text{ years}, \]

where the same typical assumptions are made as above, and the relative transverse velocity \( v_{600} \) is parametrized in units of 600 km/sec. This time scale results in discouragingly large values for stellar mass objects. However, we can expect fluctuations on much shorter time intervals. Due to the fact that the magnification distribution is highly non-linear, the sharp caustic lines separate regions of low and high magnification. So if a source crosses such a caustic line, we will observe a large change in magnification during the time it takes the source to cross its own diameter:

\[ t_{cross} = \frac{R_{source}}{v_\perp} \approx 4R_{15} v_600^{-1} \text{ months}. \]

Here the quasar size \( R_{15} \) is parametrized in units of \( 10^{15} \text{ cm} \). This time scale \( t_{cross} \) can be significantly shorter than \( t_E \).

1.2. Geometry

The typical geometry of a cosmological microlensing situation is displayed in Figure 1. The main lensing agent is a galaxy, which consists partly of stars (and other compact objects). The “macro”-lensing situation produces two (or more) images of the background quasar, separated by an angle of order one arcsecond. However, because of the graininess of the main lens, each of these macro-images consists of many micro-images, which are separated by angles of order microarcseconds, and hence are unresolvable. However, due to the relative motion between source, lens and observer, the micro-image configuration changes, and so does the total magnification, which is observable.
Figure 1. Geometry of a microlensing situation: the galaxy in the lens plane acts as a “macro-lens”, producing two separate images of the background quasar. Due to the graininess of the matter distribution in the galaxy, each macro-image is split into many micro-images. Only the total magnification of all the microimages is measurable.
1.3. History

Only a few months after the detection of the first multiply imaged quasar was published by Walsh, Carswell and Weymann (1979), Kyongae Chang and Sjur Refsdal suggested in their paper “Flux variations of QSO 0957+561 A, B and image splitting by stars near the light path”, (Chang & Refsdal 1979):

“If the double quasar QSO 0957+561 A, B is the result of gravitational lens actions by a massive galaxy, stars in its outer parts and close to the line of paths may cause significant flux changes in one year.”

Only two years later, J. Richard Gott III asked the question: “Are heavy halos made of low mass stars? A gravitational lens test”, Gott (1981). He suggests that a heavy halo made of low mass stars in the range $4 \times 10^{-4} M_\odot$ to $0.1 M_\odot$

“... should produce fluctuations of order unity in the intensities of the QSO images on time scales of 1-14 years.”

He went on to propose:

“Observations of QSO 0957+561 A, B and other quasars over time can establish whether the majority of mass in the heavy halo is in the form of low mass stars.”

In a number of further papers, the lensing effect of individual stars on the background quasar was explored; e.g., Young (1981) did some numerical simulations and applied them to the double quasar. In the year 1989, the first observational evidence for quasar microlensing was presented: Irwin et al. (1989) showed that fluctuations in image A of the quadruple quasar Q2237+0305 could not be due to intrinsic variability of the quasar. Such fluctuations could be explained by the lensing action of low-mass main sequence stars and allowed conclusions on the quasar size to be of order a few times $10^{14}$ cm (Wambsganss, Paczyński, & Schneider 1990).

1.4. Early Promises

Fluctuations in the brightness of a quasar can have two causes: they can be intrinsic to the quasar, or they can be microlens-induced. For a single quasar image, the difference is hard to tell. However, once there are two or more gravitationally lensed (macro-)images of a quasar, we have a relatively good handle to distinguish the two possible causes of variability: any fluctuations due to intrinsic variability of the quasar have to show up in all the quasar images, after a certain time delay. In fact, time delays of quasars are only measurable because quasars are variable intrinsically. (This argument could even be turned around: the measured time delays in multiple quasars are the ultimate proof of the intrinsic variability of quasars.) So once a time delay is measured in a multiply-imaged quasar system, the incoherent fluctuations can be contributed to microlensing.

There is another possibility to distinguish the two causes of fluctuations: even without measuring the time delay, it is possible to tell whether measured fluctuations are intrinsic or not: in some quadruple lens systems, the image arrangement is so symmetrical around the lens, that any possible lens model
predicts very short time delays (of order days or shorter), so that fluctuations in individual images that are longer than the (theoretical) time delay and not followed by corresponding fluctuations in the other images, can be safely attributed to microlensing. This is in fact the case of the quadruple system Q2237+0305, see below.

Early on, the papers exploring microlensing made four predictions concerning the possible scientific successes. With microlensing 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 the masses of lensing objects.

In Chapter 3 the observational results to date will be discussed in some detail. It can be stated already here 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 observational results are consistent with masses of the lensing objects corresponding to low-mass stars.

1.5. “Local Group” Microlensing versus Extragalactic Microlensing

This contribution deals mainly with quasar microlensing, where in most cases the surface mass density (or optical depth) is of order the critical one. In contrast to that, most other papers at these proceedings are concerned with the “local group” or low optical depth microlensing. Since there are a number of similarities, but as well quite some differences between these two regimes, in Table 1 the various quantities are compared to each other.

2. Theoretical Work on Cosmological Microlensing

In the situation of a multiply imaged quasar, the surface mass density (or “optical depth”) at the position of an image is of order unity. If this matter is made of compact objects in the range described above, due to the relative motion of source, lens(es) and observer, microlensing is expected to be going on basically “all the time”. In addition, this means that the lens action is due to a coherent effect of many microlenses, because the action of two or more point lenses whose projected positions is of order their Einstein radii adds in a very non-linear way.

The lens action of more than two point lenses cannot be easily treated analytically any more. Hence numerical techniques were developed in order to simulate the gravitational lens effect of many compact objects. Paczyński (1986) had used a method to look for the extrema in the time delay surface. Kayser,Refsdal, Stabell (1986), Schneider & Weiss (1987) and Wambsganss (1990) had developed and applied an inverse ray-shooting technique that produced a two-dimensional magnification distribution in the source plane. An alternative technique was proposed by Witt (1993) and Lewis et al. (1993). They solved the
### Table 1.
The important lensing properties for the two regimes of microlensing – local group vs. cosmological – are compared to each other. At the left the various properties of interest are named, in the middle and right-hand column it is listed whether these properties are known and/or the corresponding values are given for the Milky Way and the lensing galaxy, respectively.

| Property                                      | Milky Way | Lens in Q0957+561 |
|-----------------------------------------------|-----------|-------------------|
| distance to Macho?                            | no        | yes               |
| velocity of Macho?                            | no        | (no)              |
| mass?                                         | ???       | ???               |
| optical depth?                                | $\approx 10^{-6}$ | $\approx 1$       |
| 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 | Irwin et al. 1989 |

All the recent theoretical work on microlensing is based on either of these techniques.

Fluke & Webster (1999) explored analytically caustic crossing events for a quasar. Lewis & Belle (1998) showed that spectroscopic monitoring of multiple quasars can be used to probe the broad line regions. Wyithe et al. (2000a, 2000b) explored and found limits on the quasar size and on the mass function in Q2237+0305.

Agol & Krolik (1999) and Mineshige & Yonehara (1999) developed techniques to recover the one-dimensional brightness profile of a quasar, based on the earlier work by Grieger et al. (1988, 1991). Agol & Krolik showed that frequent monitoring of a caustic crossing event in many wave bands (they used 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 (1999) in a similar approach explored the effect of microlensing on two different accretion disk models. In another paper, Yonehara et al. (1998) showed that monitoring a microlensing event in X-rays can reveal structure of the quasar accretion disk as small as AU-size.

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 $\leq 10^{-2}M_\odot$ (Wambsganss et al. 2000).

3. Observational Evidence for Cosmological Microlensing

3.1. The Einstein Cross: Quadruple Quasar Q2237+0305

In 1989 the first evidence for cosmological microlensing was found by Irwin et al. (1989) in the quadruple quasar Q2237+0305: one of the components showed fluctuations, whereas the others stayed constant. In the mean time, Q2237+0305 has been monitored by many groups (Corrigan et al. 1991; Østensen et al. 1996; Lewis et al. 1998; Wozniak et al. 1999).

The most recent and most exciting results (Wozniak et al. 1999) show that all four images vary dramatically (but incoherently!), 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 (and rising?),
- $\Delta m_D \approx 0.6$ mag.

This is very encouraging news, and it calls for continuing and expanding monitoring programs for lensed quasars.

3.2. The Double Quasar Q0957+561

The microlensing results for the double quasar Q0957+561 are at the moment not quite as exciting as those for Q2237+0305. 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; Wambsganss et al. 2000). At his moment, the possibility for some small amplitude rapid microlensing cannot be excluded; however, one needs a very well determined time delay and very accurate photometry, in order to establish that (Colley & Schild 1999).
3.3. Other multiple quasars

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 et al. 2000) In particular the possibility for “radio”-microlensing appears very interesting (B1600+434, Koopmans & de Bruyn 2000 and Koopmans, these proceedings), because this was not expected in the first place, due to the presumably larger source size of the radio emission region. This novel aspect of microlensing is definitely worth pursuing in more detail.

4. Unconventional Microlensing

4.1. Microlensing in individual quasars?

There were a number of papers interpreting the variability of individual quasars as microlensing (Hawkins 1996, 1998; Hawkins & Taylor 1997). 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 fully or partly attributed to microlensing. After all, quasars are intrinsically variable (otherwise we could not measure time delays), and the amount of microlensing in single quasars must me smaller than the one in multiply imaged ones, due to the lower surface mass density. Only more observations can help solve this question.

4.2. “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.

5. Microlensing: Now and Forever?

Monitoring observations of various multiple quasar systems in the last decade have clearly established qualitatively that the phenomenon of “cosmological” microlensing exists. Uncorrelated variations in multiple quasar systems with amplitudes of more than a magnitude have been observed, on time scales of weeks to months to years. However, in order to get close 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 lightcurves (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 lightcurve shapes possible even for a fixed set of parameters, no “unique” quantitative explanation or even predictions has been achieved so far. The prospects of getting much better sampled lightcurves of multiple quasars, as shown by the OGLE collaboration, should be enough motivation to explore this regime more quantitatively in the future.

The question of the quasar structure deserves much more attention. Here gravitational lensing is in the unique situation to be able to explore an astrophysical field that is unattainable by any 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 obtain useful values for the quasar size and (one-dimensional) profile from unevenly sampled data in (not enough) different filters.

Summarized it can be said that cosmological microlensing – though still a young discipline – has already achieved part of its original goals in attacking the questions of compact (dark) matter and quasar size and structure. But there is still a lot of very interesting astrophysics out there, “in reach”. The field is definitely worthwhile pursuing with more efforts in the future – both theoretically and observationally.

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