KUIPER BELT AND OORT CLOUD OBJECTS: MICROLENSES OR STELLAR OCCULTERS?

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ABSTRACT

The occultation of background stars by foreground Solar system objects, such as planets and asteroids, has been widely used as an observational probe to study physical properties associated with the foreground sample. Similarly, the gravitational microlensing of background stellar sources by foreground mass concentrations has also been widely used to understand the foreground mass distribution. Though distinct, these two possibilities present two extreme cases during a transit: At the edge of the Solar system and beyond, the Kuiper belt and Oort cloud populations may present interesting foreground samples where combinations of occultation and lensing, and possibly both during the same transit, can be observed. To detect these events, wide-field monitoring campaigns with time sampling intervals of order tenths of seconds are required. For certain planetary occultation light curves, such as those involving Pluto, an accounting of the gravitational lensing effect may be necessary when deriving precise physical properties of the atmosphere through the associated refraction signal.

Subject headings:

1. INTRODUCTION

The occultation of background stars by foreground objects has been widely used as an observational probe to study physical properties of various Solar system constituents such as planets, asteroids, comets, and rings (for an early review, see, Elliot 1979). In addition to basic physical properties, such as the radius of the foreground object that occulted the background star, the refraction of background stellar light by the foreground planetary atmosphere provides a well utilized probe to derive certain physical properties of the lower atmosphere (see, for example, the recent review by Elliot & Olkin 1996 for further details).

On the other hand, at galactic distance scales well beyond the Solar system, foreground mass concentrations are expected to gravitationally microlens background stars ( Paczyński 1986). The microlensing of background sources by foreground objects is now well utilized to understand mass distributions in the galaxy, including potential dark matter candidates involving the so-called Massive Compact Halo Objects (MACHOs; Griest 1991). A typical microlensing observational campaign now involve continuous monitoring of million or more stellar sources towards, say, the galactic bulge and the Magellanic clouds with time sampling intervals of order tens of minutes or more (e.g., Alcock et al 1993; Udalski et al 1993).

Though occultation, with a decrease in background source flux, and microlensing, with an increase in background source flux, have been mostly discussed as two separate phenomena, the two possibilities form essentially extreme cases during the transit of a foreground source across the surface of a projected background stellar surface. In general, though, one expects signatures of both occultation and gravitational lensing to be evident for a given population of foreground sources, the nature provides a simple reason why only these two extreme cases have been observed so far: the distance scale involved is such that known objects in the Solar system always occult background sources while foreground sources at galactic distances always microlens background stars. The transition between that of an occultation to a lensing event is rapid with only a limited range of parameters where both an occultation and a lensing signature will be visible during the same transit.

The favorable condition to observe both a combination of occultation and microlens in the same foreground sample involve a projected extent to the foreground object that is of the same order as the Einstein radius associated with gravitational lensing. In the case of a pure occultation, the projected foreground source radius is larger than the Einstein radius while the opposite is true for the observation of a gravitational lensing effect. While transit events involving binary stars have been previously suggested as potential occurrences of both microlensing and occultation (Marsh 2001), favorable conditions may also be present with foreground sources in the Solar system, but at distance scales well beyond planets.

Here, we identify outer Solar system populations, such as the Kuiper belt objects (KBO; Kuiper 1951) and the Oort cloud objects (OCO; Oort 1950) as interesting samples of foreground sources where both gravitational lensing and occultation, as well as a combination of the two, can be observed when they transit background stars. In fact, KBOs have been suggested as potential occulters in a previous study where the use of transits was considered in detail to extract the small size members of this population (Roques & Moncuquet 2000). Here, we suggest that the consideration of KBOs as occulters may only apply to the currently observed KBO object population. If KBOs extend to much larger distances, as far as the Oort cloud, and contains massive members at large distances that currently probed, then there is some possibility that the distant members may in fact produce either a signature of lensing alone or a combination of lensing and occultation.

While no detailed data on the OCO population are observationally available, the currently cataloged KBO population is mostly at orbital distances between 40 and 50 AU with over $10^5$ objects of 100 km or more in size. The
total estimated mass is of order $0.08 \, M_\oplus$ (see, Luu & Jewitt 2002 for a recent review). Extending current wide-field microlensing campaigns, which have been well executed to monitor millions of stars or more on a given night (e.g., Alcock et al 1993; Udalski et al 1993), we suggest that small bodies of the outer Solar system can be detected and cataloged via similar continuous monitoring programs. Since the duration of transit events involving outer Solar system objects are of order a minute and less, sampling time intervals, however, must be at the level of few tenths of seconds instead of usual tens of minutes or more time scales currently used in galactic microlensing campaigns. Such high sampling rates, while keeping the same flux threshold levels as current surveys, are within reach with the advent of dedicated large area telescopes and continuous improvements in the instrumental front. The combined occultation and lensing measurements allow the observational data on KBO and OCO samples to be significantly extended since one is no longer sensitive to individual fluxes, as in direct imaging observations, but rather on the ability to detect and extract transit events during the monitoring of a large sample of background sources.

The discussion is organized as following. In the next section, we introduce the concept of occultation and microlensing as two extreme cases of the same transit event. We discuss potential signature of KBOs when transiting across a background stellar surface. A detailed study of the statistical signature of occultation due to KBO population is presented in Roques & Moncuquet (2000) to which we refer the reader to further details. Similarly, the paper by Agol (2002) considers the signature of an occultation and lensing during transit events that involve binary sources orbiting each other. A prior discussion on the occultation signature in a microlensing light curve, as applied to galactic lensing surveys, is available in Bromley (1996). Here, we consider the application to the Solar system as a potential way to extend our understanding of outer members which may have avoided direct detection due to low flux levels.

2. OCCULTATION AND GRAVITATIONAL LENSING

Following Narayan & Bartelmann (1999), we write the “lens equation” associated with a gravitational lensing event as

$$ \beta = \theta - \frac{\theta_E^2}{\theta}, $$

(1)

where $\theta$ corresponds to image positions given the source position, $\beta$. Here, $\theta_E$ is the angular Einstein radius for a foreground source of mass $M$ given by

$$ \theta_E = \sqrt{\frac{4GM}{c^2}} \frac{D_{ls}}{D_s D_l}, $$

$$ \approx (7.1 \text{mas}) \left( \frac{M}{M_\oplus} \right)^{1/2} \left( \frac{D_l}{100 \text{AU}} \right)^{-1/2}, $$

(2)

where we have made use of the fact that the distance between foreground lens and background source, $D_{ls} = D_s - D_l$, can be well approximated by source distance, $D_s$, with the final result only depending on the foreground lens distance, $D_l$. For a Earth mass object at a distance of 100 AU, the Einstein radius, $R_E = \Theta_E D_l$, is of order $5.1 \times 10^2 \, \text{km} (M/M_\oplus)^{1/2} (D_l/100 \text{AU})^{1/2}$. Foreground objects whose radius, $R_L$, is equal or less than the Einstein radius are expected to microlens background sources during a transit event.

Under the point mass approximation, the microlensing event involve two images. The total magnification during the transit is given by the sum of individual magnifications with a correction that accounts for the potential occultation by the foreground source (for example, Agol 2002):

$$ A_{\text{tot}} = A_- \Theta(f_1 - f_2) + A_+ \Theta(f_1 + f_2), $$

(3)

where $A_-$ and $A_+$ are magnifications associated with inner and outer images, which are identified with respect to the Einstein radius. Defining the projected lens-source angular separation in terms of the Einstein angle, $u = \beta \theta_E^{-1}$, we write

$$ A_\pm = \frac{1}{2} \left( \frac{u^2 + 2}{u \sqrt{u^2 + 4}} \pm 1 \right), $$

(4)

In equation 3, $\Theta(x)$ is the step function of $x$ with $f_1$ and $f_2$ given by

$$ f_1 = 1.0 - \left( \frac{R_L}{R_E} \right)^2 $$

and

$$ f_2 = \left( \frac{R_L}{R_E} \right) u, $$

(5)

respectively. As written, if $R_L > R_E$, the inner image (−) is occulted while the outer image (+) is also occulted when $u < R_L/R_E - R_E/R_l$. The general condition for an occultation requires that both images are occulted at all times. This depends on the impact distance of the transit

![Figure 1](image-url)
chord with respect to foreground lens center. In the case of a transit event that passes exactly through the center, the condition is $\sqrt{2}R_L > R_E$.

We illustrate several occultation light curves, with a lens source distance corresponding to the OCO population in Fig. 1. As shown, the light curves exhibit the transition from a full occultation to that of a lensing event with increasing radius, or mass, for the foreground object. For simplicity, here and throughout, we assume a density for the object equivalent to that of Pluto. In Fig. 1, we plot these light curves in terms of the angular separation, in units of Einstein angle, between the background stellar source and the foreground object. One can convert these light curves to a more practical unit, such as time, based on information related to the projected relative velocity of the foreground object across the background source as viewed from Earth. Assuming typical velocities of order 30 km sec$^{-1}$ near the ecliptic, we determine event durations of order $\sim$ 3 sec to 3000 sec for radii ranging from 100 km to 10000 km. In reality, members of the outer Solar system objects are likely to have radii that are less than 1000 km, or possibly even less than 100 km, suggesting that time durations are likely to be at the order of 10 seconds or less.

In estimating this event time duration, we have assumed that the background source radius is much less than that of the foreground object. In the event that the projected background source radius at the distance of the foreground object is larger than that of the lens, the time duration will be increased from that of the foreground source size to background source size. The actual flux ratio measured during the transit will also be determined by a combination of the flux of the background source, the flux of the foreground lens, and their projected radii at the foreground source distance. Since one expects outer Solar system objects to be significantly faint, if the background stellar radius is smaller than the source, then the fractional flux variation can be significant: In the case of an occultation, the effect can be a complete decrease in the background stellar flux. If the projected background stellar size is more than that of the foreground object, then the fractional flux difference during an occultation would be equivalent to the ratio of planet to star projected areas. This variation, however, can be tens of percent or more and not likely to be always at the few percent level or less expected for transit events that involve extra-Solar planets that occult their central stars. In the case of a lensing event, the flux increase depends on the detailed properties of the transit such as the minimum impact distance of the background source relative to foreground object center. For realistic scenarios involving minimum impact distances of order the Einstein radius, we expect fractional flux variations, in terms of an increase now, to be also of order 100%.

Thus, the limiting factor related to the detection of outer Solar system transit events is not the precision of relative photometry, as in the case of extra-Solar planetary transit searches, but rather the time separation of successive images. While current wide-field microlensing and extra-Solar transit surveys do not obtain data with time samplings at few tenths of seconds or less, for the purpose of understanding the outer Solar system, one will need imaging data separated at small time intervals. Note that high data sampling rates, corresponding to few hundreds of micro seconds, are already possible towards small sky areas with unique occultation CCD imagers developed by various groups that observe planetary occultations in the Solar system. With dedicated large area telescopes, and further developments in the experimental front, it is likely that in the near future millions of stars can be monitored on the night sky with data taken at sub second intervals.

3. DISCUSSION

We have explored the role of gravitational lensing when outer Solar system objects, mainly members of the Kuiper belt and the Oort cloud, transit background stars. The known population of KBOs, at distances of order 40 AU with sizes of order few hundred kilometers and less, will always occult background stars. Their occultation signature can be detected in monitoring campaigns involving few-meter class telescopes with time sampling intervals of order few tenths of seconds (Roques & Moncuquet 2000). While we have ignored here due to our interest in large size objects, as discussed in Roques & Moncuquet (2000), the detection rate of few kilometer size and below KBOs is partly enhanced by the diffraction effect that appears during the occultation.

At distances much larger than the currently known KBO population, the potential observability of a microlensing event significantly increases. At distances of few 10,000 AU and more, corresponding to the Oort cloud, objects with sizes of order hundreds of kilometers or more will gravitationally microlens background stars instead of simply occulting them. For certain foreground object sizes, or mass, at favorable distances, one can potentially observe a combination of an occultation and a lensing event during the same transit. The detection of an onset of a lensing event on an occultation light curve is interesting.

![Fig. 2.—](image-url)

**Fig. 2.** The occultation vs. microlensing possibilities in the outer solar system. Here, we plot the radius of the foreground object as a function of the distance, $D_l$. The solid curve shows an estimated division between occultation and microlensing possibilities which we take to be the case when $R_L \sim R_E$. For comparison, we show the known KBO population as well as the suggested distance of the Oort cloud. While known KBOs are more likely to be occulters, it is likely that potential microlensing events, or combined microlens-occultation events, can be observed towards the Oort cloud.
since the point at which the lensing signature enters allows one to measure the ratio of the foreground source radius to its Einstein radius accurately (Bromley 1996). This additional information will aid in constraining physical parameters of the foreground population beyond what is available solely from the occultation or the microlensing light curve.

Note that the estimated KBO optical depth near the ecliptic is of order $10^{-6}$ (Roques & Moncuquet 2000); this is at the same level as the microlensing optical depth towards the galactic bulge. The Oort cloud optical depth, however, is highly uncertain due to our limited knowledge on various properties of its population. The dynamical constraints, based on orbits of long-period comets, suggest a total population of $\sim 10^{12}$ with a total mass of 38 $M_{\oplus}$ (Weissman 1996); these estimates are clearly uncertain for obvious reasons. While the total mass is higher than that associated with KBOs, for the observable transit optical depth, what is required is the distribution of source sizes. If sizes are all equal, then with a mass of order $\sim 10^{14}$ g, and radii of order few tenths of kilometers, Oort cloud will remain undetectable with observations that attempt to detect transits.

The detectable transits, occultations and/or lensing, however, require the presence of objects with masses of order $\sim 10^{22}$ g or with radii of order few hundred kilometers. Note that certain constraints on the KBO population limits the size distribution of the outer KBOs, at distances between 50 and 70 AU, to be below few hundred kilometers (Allen et al 2001). Such surveys, however, are not sensitive to even massive objects with radii of thousands kilometers at distances corresponding to Oort cloud suggesting that instead of direct detection techniques, such as through imaging data, indirect techniques such as transit signatures will be needed to constrain its population. Note that the monitoring of transits involving both KBOs and OCOs can be concurrently considered except that the detection of events in monitoring data should involve the search for both a flux decrement as well as a possible increase due to a lensing event. Note that any increment due to lensing can easily be ascribed to massive bodies at large distances such that one breaks the usual degeneracy one encounters in galactic microlensing studies involving the mass and distance of the object. On the other hand, even if no lensing events are detected, any reliable upper limit on the lensing optical depth towards the Oort cloud can be used to constrain the massive end of its population and will aid in understanding the role OCOs play in the formation and evolution of the Solar system.

As we have discussed, the role of lensing on the occultation light curves of outer Solar system bodies is likely to be only limited to distant Oort cloud members. The gravitational lensing effect, however, may already be important for objects in the inner Solar system. For Pluto, at a distance of $\sim 39.5$ AU and a mass of 0.002 $M_{\oplus}$, the Einstein radius is of order $\sim 15$ km. This is small when compared to the Pluto radius of order 1200 km and leads to the naive conclusion that any effects related to lensing by Pluto can be ignored when interpreting its data. For precision calculations and parameter estimations, however, there may be an additional consequence associated with lensing. While the magnification signature may not be dominant, gravitational lensing also induce variations in astrometry, mainly a relative change in the image position with respect to the unlensed position. When interpreting light curves to derive atmospheric parameters, as was done in Elliot & Young (1992), it may be necessary to account for the shift in image position due to lensing along with variations arising from the atmospheric refraction effect. If not accounted properly, one will wrongly conclude the depth to which the light curve probes the Pluto’s atmosphere with an error that is of the same order as the size of the Einstein radius.

The best published data on an occultation by Pluto comes from the 9th June 1998 event involving the background star P8 (Millis et al 1993). At the inner most depths probed by refraction, the light curve associated with this event showed an anomalous gradient beyond a simple refractive atmosphere. This gradient has been modeled either as extinction due to a haze layer or due to an abrupt thermal gradient. A preliminary calculation of the astrometric lensing correction to the light curve depth indicated that the abrupt change in the light curve was unlikely due to gravitational lensing modifications. Recently, it was reported that several new light curves related to an occultation by Pluto has now been obtained. It will be an interesting exercise to see if these data require an accounting of the astrometric shift in the background source image during the inner depths of the occultation due to gravitational lensing.

To summarize, minor bodies of the outer Solar system will always occult background stellar sources. There is still some possibility that a distance sample of objects, such as members of the Oort cloud, will microlens background stars. Another possibility is that there will be a combined signature of an occultation and a lensing event during the same transit. These events, and occultation and lensing only events as well, can be extracted from continuous monitoring campaigns similar to those that are currently pursued to detect galactic microlensing towards the bulge and the Magellanic clouds. The data sampling intervals of a Solar system targeted campaign, however, should be at the order of few tenths of seconds and is within reach experimentally in the near future.

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