

An Implementation of the Ray Shooting Method



Feasibility tests with the robotic MONET telescopes



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Abstract

Ray shooting is a powerful but numerical costly means of solving the lens equation. Unlike purely numerical root finding techniques, ray shooting can automatically address the problem of finite size effects by defining the target area and, if necessary, weighting rays according to a limb-darkening model. This flexibility usually comes at the cost of calculating many - mostly unnecessary - rays.

The method can be accelerated by isolating the areas of the lens plane required for each data point using targets distant from singularities. After an initial estimation of parameters, a pre-calculated grid of magnification patterns can then be searched for a global minimum of chi-square.

Ray shooting on a complete grid

Light curves from the ray shooting method

In order to simulate light curves of a lensed source, the lens equation can be used directly (Quasar microlensing: Kayser et al. (1986, A&A, 166,36-52), extrasolar planets: Wambsgans (1997, MNRAS, 284, 172)). A grid of rays in the lens plane is mapped to the source plane and the magnification is calculated from the number of rays hitting the target.

Finite size effects and extrasolar planets

The shape of the light curve is affected by the finite size of the source star as illustrated in Fig. 1. Ray shooting includes finite size effects by defining the size of the target that can be hit. Physically, this information can be useful for breaking the mass degeneracy, especially for a caustic crossing event, where it provides the proper motion and thus enables one to discriminate planetary and stellar companions.

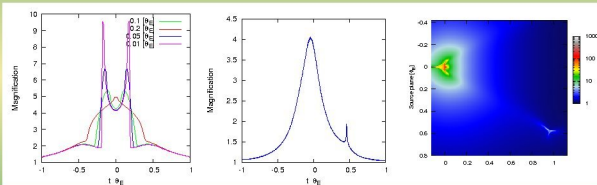


Figure 1: Finite size effects in symmetric binary microlensing light curves are illustrated for source star radii of 0.2, 0.1, 0.05, 0.001 θ_E . In addition the light curve of a potential planetary event (mass ratio $q=0.05$, lens separation $0.6 \theta_E$) and the corresponding magnification pattern is shown.

Fitting magnification patterns to light curves

For a quick parameter estimation, we use a grid of 400 pre-calculated magnification patterns representing the parameter combination of mass ratio q and separation d . The parameters Einstein time t_E , minimal impact parameter u_{\min} , orientation of the source track and time of maximum magnification t_{\max} are fitted by applying different optimization techniques.

At the lowest level, every extracted model is linearly fitted to the data set and the resulting χ^2 controls the whole fit. The final pixel grid in the source plane has a resolution of $1/300 \theta_E$. No finite size fitting is implemented yet.

Parameter estimation for Binary lens fits

Comparison of different fitting methods

Finding the best fit is a global optimization problem and a simple simplex algorithm gets stuck in local minima. Therefore the simplex is restarted with different parameters $\beta \in [10^\circ, 170^\circ]$ and for $u_{\min} \in [-1; 1]$.

Alternatively, simulated annealing with 1000 trials per step, 500 iterations per fixed temperature, a step size of 3.0, a Boltzmann constant of 20, an initial temperature of 0.6 and 2% decrease of temperature has been tried. The success and speed of this method depends also sensitively on the configuration of the random walk. The results of both methods can be finally improved with a final single simplex optimization.

Remarks	χ^2_{linear}	u_{\min}	t_E	t_{\max}	β	q	d	f
Jaroszynski (2004, AcA, 54,103-128)	5.6	-0.35	15.6	2452794.1	133.66	0.789	1.213	0.75
Simplex grid	5.6	-0.39	21.7	2452793.6	122.4	0.85	1.3	0.6
Simulated annealing	6.4	-0.30	15.1	2452793.8	134.1	0.55	1.2	0.74
Final simplex	4.5	-0.32	16.4	2452793.5	132.4	0.6	1.2	0.73

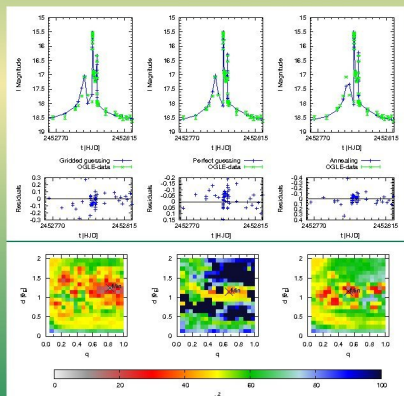


Figure 3: Fits for the binary microlensing event OGLE-2003-BLG-170 with different methods along with the corresponding residuals and the reduced χ^2_{linear} maps. A grid of initial parameters for a simplex fit (left), single simplex fits (middle), and simulated annealing fits with estimated parameters from a PLPS model (right).

Pointwise ray shooting

Pointwise ray shooting

Including finite size effects and limb darkening requires the definition of target apertures along the observed light curve. For some part of the source track, the solution of the binary lens equation can be determined numerically by finding the roots of a complex, 5th order polynomial (Witt & Mao, ApJ, 447, L105-L108). The complete solution of the lens equation can be used to calculate the Jacobian determinant of the lens equation and thus the Magnification of a point source.

Finite source effects can be taken into account using the convolution of point source magnification patterns with a limb darkening model, but for a large number of lenses and complex lens geometries source effects can be more easily obtained from ray shooting. However, numerical accuracy requires a large number of rays.

In order to accelerate the simulation, regions on the lens plane, which cannot be mapped to the source star, can be neglected (cf. Rattenbury & Bond (2002, MNRAS, 335, 159-169)). In contrast to this approach, we try to select the part of the lens plane that has to be included by using solutions of the lens equation.

Fig. 2 illustrates the method and its obstacles for the well known point lens point source model. Close to the singularities, overlapping and tangent sources impose difficulties because no valid lens plane region can be found.

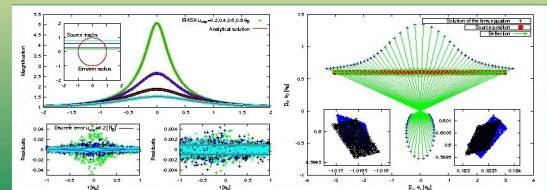


Figure 2: The simulation of PLPS models is shown (left). Residuals with variable and constant ray density demonstrate that close to the lens more rays are wasted if the numerical errors shall remain constant. The right panel shows the superposition of randomized rays.

Test observations with MONET

Observations and data reduction

Test observations have been carried out using the MONET/North telescope (30° North, 104° West). The objects were visible through 2 airmasses and the average seeing was 2.2 arcsec for OGLE-2007-BLG-006 and 2.6 arcsec for OGLE-2007-BLG-050.

Difference imaging has been tested using ISIS 2.2 (Alard & Lupton 1998, ApJ 503, 325), TRIPP (Israel et al. 2007, AN, 328, 16-24) and DIA (Wozniak 2000, Acta Astronomica 50, 421). The latter results are used in Fig. 5.

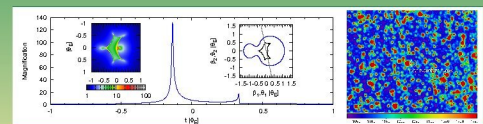


Figure 4: The simulated light curve along with source track and magnification pattern for the parameters in Tab. 2 are shown. The right panel shows the reference image from the MONET follow-up observations of OGLE-2007-BLG-006.

Follow-up observations with MONET

The test objects were selected using the Planet Lens OPTimisation page (PLOP). No absolute magnitudes are available yet and thus our data is linearly fitted to models for OGLE data. The binary event OGLE-2007-BLG-006 has been fitted by using the pre-calculated magnification patterns and for OGLE-2007-BLG-050 a uniform source profile has been used (Witt & Mao 1994, ApJ, 430, 505-510).

Object	χ^2_{linear}	u_{\min}	t_E	t_{\max}	β	q	d	f	r_s
OGLE-2007-BLG-006	4.2	0.021	34.075	2454172.6	183.7	0.25	1.0	1.0	-
OGLE-2007-BLG-050	334.8	0.0031	52.2	2454221.30	-	-	-	1.0	-
OGLE-2007-BLG-050	48.7	0.0021	66.0	2454221.97	-	-	-	0.76	0.0044

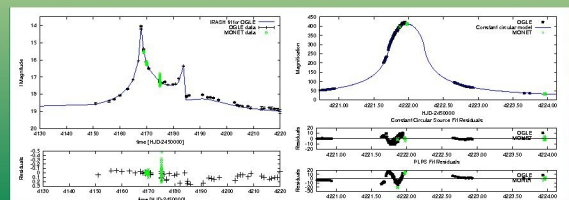


Figure 5: The light curves of OGLE-2007-BLG-006 (left) and OGLE-2007-BLG-050 (right), including linear fitted MONET data, are shown. The binary fit was obtained from the extraction of light curves without blending.