Microlensing in Andromeda

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The compact object content of the M31 halo

Based on:
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We present the microlensing analysis of a data set obtained during four observing seasons at the Isaac Newton Telescope (INT) on La Palma. Using a fully automated method we identify 14 candidate microlensing events, 3 of which are reported here for the first time; 10 overlap with our previous analysis of a subset of the current data set. Observations obtained at the Mayall 4m telescope at Kitt Peak are combined with the INT data to produce composite lightcurves for these candidates. The results from the survey are compared with theoretical predictions for the number and distribution of events. These predictions are based on a Monte Carlo calculation of the detection efficiency and self-consistent disk-bulge-halo models for M31. The models provide the full phase-space distribution functions (DFs) for the lens and source populations and are motivated by dynamical and observational considerations. They include differential extinction and span a wide range of parameter space characterized primarily by the mass-to-light ratios for the disk and bulge. For most models, the observed event rate is consistent with the rate predicted for self-lensing — a MACHO halo fraction of 30% or higher can be ruled at the 95% confidence level. The event distribution does show a large near-far asymmetry hinting at a halo contribution to the microlensing signal. Two candidate events are located at particularly large projected radii on the far side of the disk. These events are difficult to explain by self lensing and only somewhat easier to explain by MACHO lensing. A possibility is that one of these is due to a lens in a giant stellar stream.
5.1 Introduction

Compact objects that emit little or no radiation form a class of plausible candidates for the composition of dark matter halos. Examples include black holes, brown dwarfs, and stellar remnants such as white dwarfs and neutron stars. These objects, collectively known as Massive Astrophysical Compact Halo Objects or MACHOs, can be detected indirectly through gravitational microlensing wherein light from a background star is amplified by the spacetime curvature associated with the object (Paczynski 1986).

During the past decade several groups have used microlensing surveys to find evidence for the existence of a large population of MACHOs in the dark halo surrounding the Milky Way and, more recently also the Andromeda galaxy, M31. The Milky Way halo was probed by the microlensing surveys toward the Large and Small Magellanic Clouds performed by the MACHO (Alcock et al. 2000) and EROS (Lasserre et al. 2000; Afonso et al. 2003) collaborations. While both collaborations detected microlensing events, they reached different conclusions. The MACHO collaboration reported results that favour a MACHO halo fraction of 20%. On the other hand, the results from EROS are consistent with no MACHOs and imply an upper bound of 20% for the MACHO halo fraction. They do leave open the question of whether MACHOs make up a substantial fraction of halo dark matter and illustrate an inherent difficulty with microlensing searches for MACHOs, namely that they must contend with a background of self-lensing events (e.g., lensing by stars in the Milky Way or Magellanic clouds), variable stars, and supernovae. The Magellanic Cloud surveys are also hampered by having only two lines of sight through the Milky Way halo.

Microlensing experiments toward M31 have important advantages over the Magellanic Cloud surveys (Crotts 1992). Due to the high density of background stars and the availability of lines-of-sight through dense parts of the M31 halo, the microlensing rates are greatly enhanced. Furthermore, microlensing by compact objects in the M31 halo induces a microlensing optical depth distribution that is strongly asymmetric with respect to the major axis of M31, because the path length through the halo is much longer toward to far side of the disk than toward the near side. Therefore, if the M31 halo contains a significant population of compact objects the microlensing event rate should show a similar asymmetry (Gyuk & Crotts 2000; Kerins et al. 2001; Baltz et al. 2003).

Unlike stars in the Magellanic Clouds, those in M31 are largely unresolved, a situation that presents a challenge for the surveys but one that can be overcome by a variety of techniques. To date microlensing events toward M31 have been reported by four different collaborations, VATT-Columbia (Uglesich et al. 2004), MEGA (de Jong et al. 2004), POINT-AGAPE (Paulin-Henriksson et al. 2003; Belokurov et al. 2005; Calchi Novati et al. 2005) and WeCAPP (Riffeser et al. 2003).

The MEGA collaboration is conducting a microlensing survey in order to quantify the amount of MACHO dark matter in the M31 halo. Observations are carried out at a number of telescopes including the 2.5m Isaac Newton Telescope (INT) on La Palma, and, on Kitt Peak, the 1.3m McGraw-Hill, 2.4m Hiltner, and 4m Mayall telescopes. The first three seasons of INT data were acquired jointly with the POINT-AGAPE collaboration but the data reduction and analysis have been performed independently.

In chapter 3 we presented 14 candidate microlensing events from the first two seasons of INT data. The angular distribution of these events hinted at a near-far asymmetry albeit with low statistical significance. Recently, the discovery that the observed distribution of variable
stars also shows a near-far asymmetry (An et al. 2004a) has complicated the interpretation of the M31 microlensing results. However, since the asymmetry in the variable stars is most likely caused by extinction (An et al. 2004a; chapter 4), it is possible to correct for this and still use the distribution of microlensing events to study the contribution of halo lensing to the total microlensing signal.

In this chapter we present our analysis of the four-year INT data set. Compared to the analysis in chapter 3 the extension of the data set from two to four years is only one of several important improvements. We also improve upon the photometry to reduce the sensitivity to crowding of variable sources and upon the data reduction in order to reduce the number of spurious variable-source detections. Furthermore we fully automate the selection of microlensing events and model the detection efficiency through extensive Monte Carlo simulations. Using these efficiencies, we compare the sample of candidate microlensing events with theoretical predictions for the rate of events and their angular and timescale distributions. These predictions are based on new self-consistent disk-bulge-halo models (Widrow & Dubinski 2005) and a model for differential extinction across the M31 disk. The models are motivated by photometric and kinematic data for M31 as well as a theoretical understanding of galactic dynamics. Our analysis shows that the observed number of events can be explained by self-lensing due to stars in the disk and bulge of M31 though we cannot rule out a MACHO fraction of 30%.

The INT data set and the reduction methods are described in section 5.2. Section 5.3 describes Monte Carlo simulations of artificial microlensing events. The results of these simulations are used to set the selection criteria for microlensing events and to determine the detection efficiency for microlensing. How our sample of microlensing events was selected is dealt with in section 5.4, followed by a description of the sample in section 5.5. Section 5.6 shows how the detection efficiency is determined using the Monte Carlo results and the automated microlensing selection procedure. Our differential extinction model that is used in our theoretical models is presented in section 5.7. The model calculations are described in section 5.8. In section 5.9 we discuss the comparison of the candidate microlensing events with the theoretical predictions. Our conclusions are summarized in section 5.10.

5.2 Data acquisition and reduction methods

The layout of the WFC chips on M31 is shown in figure 5.1, covering a large part of the far side (SE) of the disk of M31, and part of the near side. The four 2048x4100 pixel chips with a pixel scale of 0.333", offer a field of view of approximately 0.25°. Observations were done during four six-month observing seasons (August-January). Because the WFC is not always mounted on the INT, the epochs tend to cluster in blocks of two to three weeks. During the first (99/00) observing season exposures were taken in three filters, r, g, and i, which are close to the Sloan filters. During the other observing seasons (00/01, 01/02 and 02/03) only the r' and i' filters were used. Observations were spread equally over both fields. For the 99/00 season the exposure time per night ranges between 5 and 30 minutes and is typically 10 minutes per field and filter. During the other seasons exposure times are 10 minutes per field and filter by default.

Standard data reduction, including bias subtraction, trimming, and flatfielding was performed in IRAF. For the detection and photometry of variable objects in these highly crowded fields we use the Difference Image Photometry (DIP) method as described by Tomaney &
Crotts (1996). This method involves subtracting individual images from a high quality reference image, resulting in difference images in which variable objects show up as residuals. Most operations are done in IRAF, using the DIFIMPHOT package written primarily by Austin Tomaney.

**Astrometric registration and stacking of images**

All images are transformed to a common astrometric reference frame. By stacking high quality images from the 99/00 season, a high signal-to-noise reference image was made. Per night all exposures are combined separately for each band. Each epoch corresponds to the combination of all frames taken in the same band in one night. The Julian date of the epoch is taken as the weighted average of the Julian dates of the individual frames.

**Image subtraction**

From the single epoch images the high signal-to-noise reference image is subtracted, after photometric calibration and matching of the point spread function (PSF) between the images (Tomaney & Crotts 1996). The shape of the PSF is measured from bright, unsaturated stars in the images that are being matched. By dividing the PSFs in Fourier space a convolution kernel is calculated with which the better seeing image (usually the reference image) is degraded. In regions with very high surface brightness the image subtraction is not of very high quality. For this reason we exclude a small part of the south field that is located in the bulge and has a very high background level. This region is indicated in figure 5.1.

**Variable object detection**

The resulting difference images are dominated by shot noise in which variable sources show up as positive or negative residuals, depending on the flux difference of the object between the single epoch image and the reference image. Due to fringing, the $i'$ difference images are of poorer quality than the $r'$ difference images. SExtractor (Bertin & Arnouts 1996) is used to detect residuals in all $r'$ difference images. Residuals are defined as groups of at least four connected pixels that all are at least $3\sigma$ above or below the background. The catalogues with residuals are cross-correlated to obtain a catalogue with all variable objects in the surveyed area.
Table 5.1 – Overview of the number of epochs used for each field and filter. F1 is the north field and F2 is the south field.

<table>
<thead>
<tr>
<th></th>
<th>r' North</th>
<th>r' South</th>
<th>i' North</th>
<th>i' South</th>
</tr>
</thead>
<tbody>
<tr>
<td>99/00</td>
<td>48</td>
<td>50</td>
<td>21</td>
<td>18</td>
</tr>
<tr>
<td>00/01</td>
<td>58</td>
<td>57</td>
<td>66</td>
<td>62</td>
</tr>
<tr>
<td>01/02</td>
<td>28</td>
<td>30</td>
<td>27</td>
<td>28</td>
</tr>
<tr>
<td>02/03</td>
<td>35</td>
<td>32</td>
<td>33</td>
<td>30</td>
</tr>
<tr>
<td>Total</td>
<td>169</td>
<td>169</td>
<td>147</td>
<td>138</td>
</tr>
</tbody>
</table>

fields. As a first selection to get rid of noisy detections, we demand that objects have to be detected in at least two epochs.

• **Lightcurves and Epoch quality**

Lightcurves for the variable sources are obtained by performing PSF fitting photometry on the residuals in the difference images, using the PSF shape measured from the bright unsaturated stars. An aperture of 0.5 FWHM is used, smaller than in the analysis in chapter 3 to reduce the noise introduced by nearby variable stars. Several epochs turned out to give problematic difference images for a number of different reasons. Epochs with seeing worse than 2.0” do not give clean difference images; from seven epochs all data were discarded for this reason, and for twelve epochs part of the data. In some cases the images were overexposed, causing the PSF determination to fail, forcing us to discard seven epochs completely and part of the data from seven more epochs. During the 00/01 and 01/02 season there were problems with inaccurate guiding in a number of epochs. In two epochs the guiding failed completely and these were discarded.

Lightcurves were also produced at “empty” positions, i.e. positions where no variability was detected. These lightcurves were fit to a flat line to check the error bars on the fluxes derived from statistics of the PSF fitting photometry. For each epoch, the distribution of the deviations from the flat lightcurve fits weighted by the error bar returned by the photometry routine was examined. In some cases this distribution showed broad non-gaussian wings, and these epochs were discarded. Typically they were associated either with highly variable seeing between the individual exposures or inaccurate guiding. In other cases, the normalized error distribution was gaussian, but with dispersion higher than one. In these cases the error bars were renormalized appropriately.

In total, approximately 19% of the 209 observed epochs in r' and 22% of the 183 observed epochs in i' are discarded. The typical number of epochs that were left after the procedure described above are tabulated in table 5.1 for each filter and field for all seasons. From these epochs, lightcurves (in r' and i') were constructed for the 105,447 variable objects that were detected (in r').

### 5.3 Monte Carlo simulations

This section describes the extensive simulations of microlensing events that we perform, the results of which are used in the following sections. The Monte Carlo simulations serve two purposes, namely to help in constructing robust criteria for identifying microlensing events in the real data, and to determine the detection efficiency for microlensing events. The details of the procedure follow a review of microlensing basics and terminology.
5.3.1 Microlensing lightcurves

The standard lightcurve shape of a single lens microlensing event is described by (Paczynski 1986):

\[ F(t) = F_0 \times A(t) = F_0 \times \frac{u^2 + 2}{u\sqrt{u^2 + 4}} \]  

(5.1)

where \( F_0 \) is the baseline, unlensed flux, \( A(t) \) is the amplification, and \( u \) is the projected distance between the lens and the source, in units of the Einstein radius. Finite source effects are ignored. This Einstein radius depends on the geometry of the system and the mass of the lens and in the lens plane is given by:

\[ R_E = \sqrt{\frac{4Gm}{c^2} \frac{D_{OL}D_{LS}}{D_{OS}}} \]  

(5.2)

where \( m \) is the lens mass and the D’s are the distances between observer, lens and source. Note that the amplification is always 1 or higher and independent of wavelength, meaning that microlensing is in principle achromatic and conserves the colour of the source. If the relative motion of lens and source is uniform, then \( u \) can also be written as:

\[ u(t) = \sqrt{\beta^2 + \left( \frac{t - t_{\text{max}}}{t_E} \right)^2} \]  

(5.3)

where \( \beta \) is the impact parameter in units of \( R_E \), \( t_{\text{max}} \) the time of maximum amplification and \( t_E \) the Einstein time. This is defined as the time it takes the source to cross \( 1R_E \).

In classical microlensing the measured lightcurves contain contributions from unlensed sources. Blending, as this effect is known, changes the shape of the lightcurve and can also spoil the achromaticity implicit in equation 5.1. We measure flux differences from difference images that are created by subtracting a reference image. Any flux from unlensed sources is also subtracted and no longer present in the difference images. Blending is therefore not a problem, unless the unlensed sources are variable themselves. In that case the blending of the variable sources will be variable with time and cause an unstable baseline.

For a difference image the microlensing lightcurve takes the form

\[ \Delta F(t) \equiv F(t) - F_{\text{ref}} = \Delta F_{\text{bl}} + F_0 \times (A(t) - 1) \]  

(5.4)

where \( F_{\text{ref}} \) is the reference image flux and \( \Delta F_{\text{bl}} \equiv F_0 - F_{\text{ref}} \) is the baseline flux. Thus, if in the reference image the source is not lensed, \( F_{\text{ref}} = F_0 \) and therefore \( \Delta F_{\text{bl}} \equiv 0 \). Only if the source is amplified in the reference image will \( \Delta F_{\text{bl}} \) be non-zero and negative.

For unresolved sources, a situation known as pixel lensing (and the one most applicable to stars in M31), those microlensing events that can be detected typically have high amplification. In the high amplification limit, \( t_E \) and \( \beta \) are highly degenerate (Gould 1996; Baltz & Silk 2000) and difficult to extract from the lightcurve. It is therefore advantageous to parameterize the event duration in terms of the half-maximum width of the peak,

\[ t_{\text{FWHM}} = t_E \cdot w(\beta) \]  

(5.5)

where

\[ w(\beta) = 2\sqrt{2f(f(\beta^2)) - \beta^2} \]  

(5.6)

with

\[ f(x) = \frac{x^2 + 2}{\sqrt{x(x+4)}} - 1 \]  

(5.7)

(Gondolo 1999). \( w(\beta) \) has the limiting forms \( w(\beta \ll 1) \approx \beta \sqrt{x} \) and \( w(\beta \gg 1) \approx \beta(\sqrt{2} - 1)^{1/2} \).
5.3.2 Simulation parameters

The parameters that characterize microlensing events can be divided into “microlensing parameters” such as $\beta$, $t_{\text{max}}$, and $t_E$ and parameters that describe the source stars such as intrinsic brightness $F_{0r}$, $r'-i'$ colour $C$, and position in M31. Because we sample many lines-of-sight across the face of M31 and all types of stars can in principle serve as sources for microlensing, our simulations have to cover a large parameter space.

For each simulation the $t_{\text{FWHM}}$, $F_{0r}$ and $C$ are fixed, yielding a set of microlensing events of a certain type of source star with the same peak width. The other important parameters, $t_{\text{max}}$ and $\beta$ are randomized within certain ranges. The choice of simulation parameters is summarized in table 5.2 and motivated below.

- **Peak times and baseline fluxes**
  Peak times are restricted to the observing seasons, since one of the microlensing selection criteria is that the peak of an event should lie within one of the observing seasons. We let $t_{\text{max}}$ vary randomly between August 1st and January 31st in either of the four INT observing seasons. The reference images relative to which the photometry is measured are constructed from exposures obtained during the first season. Microlensing events that peak in the first season can therefore have a reference flux that is above the baseline level, so that the baseline flux $\Delta F_{\text{ref}} \equiv F_0 - F_{\text{ref}}$ is negative. For artificial events peaking in the first season the correct reference flux is calculated, so that the correct (negative) baseline value can be used. Events peaking in the other observing seasons have a zero baseline value.

- **Event durations**
  Limits on the duration of detectable events follow naturally from the observational setup of the survey. The lower limit is determined by the closest spacing of the observations. Since the INT exposures are combined per night, events with a $t_{\text{FWHM}}$ shorter than 1 day are practically undetectable, except for very high amplifications. The peaks of events with $t_{\text{FWHM}}$ approaching the length of the observing season cannot be sampled properly, so that their selection probability decreases linearly with $t_{\text{FWHM}}$. We simulate events at six discrete values of $t_{\text{FWHM}}$ of 1, 3, 5, 10, 20 and 50 days.

- **Source fluxes and colours**
  In our microlensing survey we measure flux differences with respect to a template image. This difference flux is the product of the magnification due to the microlensing and the intrinsic flux of the lensed source. Thus, although all stars at a given location in M31 have the same probability of being magnified by a certain factor, it is easier to detect microlensing of brighter stars. On the other hand, fainter stars are more abundant, making microlensing of fainter stars more likely to occur. We have to decide which range of the source luminosity function is responsible for most of the detectable microlensing events.

  The maximum flux difference during a microlensing event is given by

  $$\Delta F_{\text{max}} = F_0 \times \left( \frac{\beta^2 + 2}{\beta \sqrt{\beta^2 + 4}} - 1 \right)$$

where $F_0$ is the intrinsic flux of the source and $\beta$ is the impact parameter in units of the Einstein radius. To be detected, $\Delta F_{\text{max}}$ should exceed the detection threshold, $F_{\text{det}}$. This lower limit on $\Delta F_{\text{max}}$ implies an upper bound on $\beta$ which, through equation 5.8, is a function of $F_0$. We therefore define an upper limit to $\beta$ as: $\beta_u(F_0/F_{\text{det}})$. Thus, the probability that a given source gives a detectable $\Delta F_{\text{max}}$ scales with $\beta_u^2$. 


In figure 5.2 we show both the brighter part of the R-band luminosity function from Mamon & Soneira (1982) and the product of this luminosity function with $\beta_u^2$ assuming a detection threshold of 1 ADU s$^{-1}$ in $r'$. This distribution peaks at an absolute R-band magnitude of approximately 0, implying that most detectable microlensing events will have sources that are Red Giant Branch (RGB) stars.

Based on these considerations we decide to use source stars with a number of discrete $r'$ fluxes between 0.01 and 10 ADU s$^{-1}$. Typical $r'-i'$ colours of RGB stars range between 0.5 and 2.0. We simulate events with $r'-i'$=0.75. To check the dependence on colour of the detection efficiency, we also simulate events with colour $r'-i'$=1.25 for part of the field.

- **Impact parameters**
  There is no sense in simulating events we know we cannot detect. Therefore we let the impact parameter $\beta$ vary randomly between 0 and the appropriate maximum value $\beta_u$ for each $r'$ flux. Table 5.2 summarizes the fluxes and $\beta_u$ for which simulations were performed.

- **Position in M31**
  The detection efficiency and lightcurve quality vary with position in M31 for several reasons. Photometric sensitivity depends on the amount of background light from the galaxy, lowering the efficiency in the bright central parts of M31. The surface density of variable stars is also higher in the central parts, making the difference images more crowded with variable star residuals. This influences the photometry, adding noise to the microlensing lightcurves.

  To sample the whole observed area in a systematic way and avoid overlap between individual simulated events, we place them on a grid with 45 pixels (15") separation between the events. Each simulation then has 3916 artificial events per chip. The grid is shifted randomly as a whole for each simulation run by a maximum of 10 pixels in either way.
5.3.3 Simulation method

Simulations are done per CCD. In each simulation 3916 artificial microlensing events are added to the $r'$ and $i'$ difference images of a certain CCD. Input parameters are the $t_{\text{FWHM}}$, intrinsic $r'$ flux $F_{0,r}$, colour $C$ and the difference images and accompanying files. The first step is the generation of the parameters of the events to be simulated and the random shift of the grid on which the events are placed. For each event the $t_{\text{max}}$, $\beta$ are randomly chosen as described above. Because the reference image is built up of images from the first season, events that peak during the first season can have a negative baseline flux. If $t_{\text{max}}$ happens to lie in the first season the baseline flux is also calculated; if $t_{\text{max}}$ lies in one of the other seasons, the baseline is zero.

The artificial events are then added as residuals into the difference images. When adding a residual to a difference image, the shape of the PSF in the subregion of the difference image is used. Photon noise is also included in the residuals.

After this, the same pipeline is used for the analysis of the modified difference images: variable objects are detected and for all detected artificial events lightcurves are built. The lightcurves are used to define the exact microlensing selection criteria. They also are used to define the detection efficiency for microlensing events.

5.4 Microlensing event selection

Of the 105,447 variable sources in our data set, the vast majority are variable stars. We need an automated method to select the lightcurves that are consistent with microlensing. This is necessary both because of the large number of lightcurves as well as because only then the detection efficiency can be properly modeled. Our selection procedure is aimed at recognizing lightcurves with the two main characteristics of microlensing events caused by a single lens: a flat baseline with a single peak with a certain characteristic shape. We also employ some criteria on the sampling of the lightcurves to ensure enough information is available for each source.

Recognition of the right lightcurves is based on the $\chi^2$ statistic that measures the goodness-of-fit of an observed lightcurve to equation 5.4. This fit is done simultaneously to the $r'$ and $i'$ lightcurves of a source and involves seven free parameters: $t_{\text{max}}$, $\beta$, $t_E$, $F_{0,r}$, $F_{0,i}$, $\Delta F_{\text{bl},r}$, and $\Delta F_{\text{bl},i}$. To increase computing speed we first obtain rough estimates for $t_{\text{max}}$ and $t_E$ from the $r'$ lightcurve and then perform the full seven-parameter fit. Other information that will be used for the microlensing candidate selection is also recorded, for example the $\chi^2$ of a flat line fit to the lightcurve, and information about how well the peak of the lightcurve is sampled.

Gravitational lensing is achromatic and therefore the observed colour of a star undergoing
Figure 5.3 – Plots of $\Delta \chi^2 / N$ versus $\chi^2 / N$. (a) For simulated events with a $t_{\text{FWHM}}$ of 50 days, (b) a $t_{\text{FWHM}}$ of 10 days, (c) a $t_{\text{FWHM}}$ of 1 day, and (d) for the actual data from 1 chip.

Microlensing remains constant, in contrast with the colour of certain variables. While we do not impose an explicit achromaticity condition, changes in the colour of a variable source show up as a poor simultaneous $r'$ and $i'$ fit. Because many red variable stars vary little in colour, as defined by measurable differences in flux ratios, the lightcurve shape and baseline flatness are better suited for distinguishing microlensing events from long period variable stars (LPVs) than a condition on achromaticity.

- **Peak and lightcurve sampling**
  Lightcurves must contain enough information for the seven-parameter fit to be used as a reliable indicator of their shapes. Both the baseline and the peak of a microlensing event should be sampled adequately by the data points. We therefore impose the following conditions:
  1. both the $r'$ and $i'$ lightcurves contain at least 100 data points.
  2. the peak contains either at least 4 points more than $3\sigma$ above the baseline in the $r'$ lightcurve, or at least more than 2 points in $r'$ and more than 1 point in $i'$ that are more
Figure 5.4 – $\Delta \chi^2 / N$ versus $\chi^2 / N$ for variable sources that satisfy selection criteria (1), (2) and (3) for peak and lightcurve sampling. The solid line indicates criteria (4) and (5) for peak significance and goodness of fit. Criterion (5) depends on the number of points in the lightcurves, and the line drawn here is for $N=309$, the typical number of available data points per source. Two candidate events with higher $\Delta \chi^2 / N$ are indicated with arrows, labeled with their $\Delta \chi^2 / N$ value.

than $3\sigma$ above the baseline.

(3) The top half of the peak should lie completely within a period with dense time sampling.

Sufficient baseline sampling is ensured by condition (1), while peak sampling is controlled by conditions (2) and (3). In (2), the $r'$ data is weighted more heavily than the $i'$ data because it is generally of higher quality and because $i'$ was not sampled as well during the first season. For (3) we define the top half of the peak as that part where the difference flux is more than half of the maximum peak difference flux. There are periods of several weeks in the third and fourth season in which we do not have data due to bad weather. This criterium ensures that at least for relatively long events both part of the rising and part of the declining side of the peak are sampled. The periods we use are the following: 01/08/1999-13/12/1999, 04/08/2000-23/01/2001, 13/08/2001-16/10/2001, 01/08/2002-10/10/2002, and 23/12/2002-31/12/2002.

- Peak significance and $\chi^2$ constraints

With sufficient information about the lightcurve shape available, we can use the $\chi^2$ values of the microlensing fits to select lightcurves that are consistent with microlensing. We also use a measure of the significance of the peak, $\Delta \chi^2 \equiv \chi^2_{\text{flat}} - \chi^2$ where $\chi^2_{\text{flat}}$ is the $\chi^2$-statistic for the fit of the observed lightcurve to a flat line. The two conditions are:

(4) $\Delta \chi^2 > 1.5N$

(5) $\chi^2 < (N - 7) f (\Delta \chi^2) + 3(2(N-7))^{1/2}$, where $f(\Delta \chi^2) = \Delta \chi^2 / 100 + 1$.

These $\chi^2$ cuts are motivated by the Monte Carlo simulations of artificial microlensing events. Figure 5.3 shows the distribution of artificial events with $t_{\text{FWHM}} = 50, 10,$ and 1 days (panels a, b, and c respectively) and for all variable sources in one of the CCDs (panel d). Conditions (4) and (5) are also indicated in the figure assuming $N = 309$ though in practice $N$ can be different for individual lightcurves. Condition (4) is meant to filter out peaks due to noise or variable stars, while condition (5) corresponds to a $3\sigma$-cut in $\chi^2$ for low signal-to-noise events. The $\chi^2$ cut in (5) increases with increasing $\Delta \chi^2$. As can be seen from panels (a)
through (c) of figure 5.3, the $\chi^2$ of the microlensing fits to the simulated events increases systematically with $\Delta \chi^2$. This effect is caused by the fact that the photometry routine in DIFIMPHOT seems to underestimate the error in the flux measurement for high flux values. Relaxing the $\chi^2$ cut for high signal-to-noise events also allows for the selection of events with secondary effects such as parallax or close caustic approaches.

After applying conditions (1)-(3) to our data set of 105,447 variable sources, we are left with 28,667 sources. In figure 5.4 we plot $\chi^2$ versus $\Delta \chi^2/N$ for these well-sampled sources. Conditions (4) and (5) are indicated, again assuming $N = 309$. Applying (4) and (5), we arrive at our final sample of 14 candidate microlensing events, that are described in detail in the next section.

### 5.5 Microlensing event sample

In table 5.3 the coordinates and maximum measured brightnesses of the events are given as well as some fit parameters. Figure 5.5 shows the positions of the events in the INT fields. In appendix 5.A we show for all candidate events the $r'$ and $i'$ lightcurves, zooms on the peak region and a plot of the $r'$ versus the $i'$ flux, as well as thumbnails from the difference images. Also shown in the lightcurves are R- and I-band measurements from the 4m Mayall telescope at Kitt Peak (KP4m). The fits drawn in the lightcurves and the fit parameters in table 5.3 are taken from the fits to only the INT data; the KP4m points are just informative.

#### 5.5.1 Sample description

Compared to the sample presented in chapter 3, four candidate microlensing events have disappeared and four new events have been found. Candidates MEGA-ML-4, -5, -6, and -12 have turned out not to be microlensing events, but variable stars that fluctuate in the fourth season. All other candidates from the previous two-year sample are “rediscovered” in the current, more robust analysis. Furthermore, we detect four more candidate events: MEGA-ML-15, -16, -17, and -18. Event MEGA-ML-16 peaks in the first season and is the same as PA-99-N1, presented by Paulin-Henriksson et al. (2003). The other new events all peaked in the fourth observing season and are reported here for the first time.

In chapter 3, blending of variable stars introduced noisy baselines, causing us to miss event PA-99-N1 found by Paulin-Henriksson et al. (2003). For this reason we now use a smaller aperture of size 0.5 FWHM and this efficiently reduces the noise, as testified by the fact that PA-99-N1 is now included in our sample as MEGA-ML-16. Nevertheless, some variable star blending is unavoidable, especially in the crowded regions close the the center of M31, where every resolution element will have some flux of faint, unresolved variable stars. A good example is provided by event MEGA-ML-3, which has a noisy baseline, in the KP4m data as well as in the INT data. A faint positive residual is visible in the 1997 KP4m difference image shown in figure 5.6. The residual is located one pixel ($0.21\arcsec$) from the event and is likely due to a variable star. It corresponds to the data point in the lightcurve $\sim 1000$ days before the event and well-above the baseline (see figure 5.23). The KP4m data point from 2004 is also above the baseline but in this and other difference images, no residual is visible. This implies that very faint variable stars will influence the photometry even when they are too faint to be detected in the difference images. Noisy baselines are therefore unavoidable in the high surface brightness parts of our field.

All candidate events are fitted well by the simultaneous $r'$ and $i'$ microlensing fit. Events
Table 5.3 – Coordinates, highest measured difference flux, and some fit parameters for the 14 candidate microlensing events.

<table>
<thead>
<tr>
<th>Candidate event</th>
<th>RA (J2000)</th>
<th>DEC (J2000)</th>
<th>$\Delta r'$ (mag)</th>
<th>$t_{\text{max}}$ (days)</th>
<th>$t_{\text{FWHM}}$ (days)</th>
<th>$\chi^2/N$</th>
<th>$\Delta \chi^2/N$</th>
<th>$F_{0,r} \text{ (ADU s}^{-1})$</th>
<th>$r^i-r'$ (mag)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MEGA-ML 1</td>
<td>0:43:10.54</td>
<td>41:17:47.8</td>
<td>21.8±0.4</td>
<td>60.1±0.1</td>
<td>5.4±7.0</td>
<td>1.12</td>
<td>1.91</td>
<td>0.1±0.3</td>
<td>0.6</td>
</tr>
<tr>
<td>MEGA-ML 2</td>
<td>0:43:11.95</td>
<td>41:17:43.6</td>
<td>21.51±0.06</td>
<td>34.0±0.1</td>
<td>4.2±0.7</td>
<td>1.06</td>
<td>2.48</td>
<td>3.4±1.7</td>
<td>0.3</td>
</tr>
<tr>
<td>MEGA-ML 3</td>
<td>0:43:15.76</td>
<td>41:20:52.2</td>
<td>21.6±0.1</td>
<td>420.03±0.03</td>
<td>2.3±2.9</td>
<td>1.14</td>
<td>2.11</td>
<td>0.08±0.21</td>
<td>0.4</td>
</tr>
<tr>
<td>MEGA-ML 7</td>
<td>0:44:20.89</td>
<td>41:28:44.6</td>
<td>19.37±0.02</td>
<td>71.8±0.1</td>
<td>17.8±0.4</td>
<td>1.98</td>
<td>256.9</td>
<td>6.8±0.4</td>
<td>1.5</td>
</tr>
<tr>
<td>MEGA-ML 8</td>
<td>0:43:24.53</td>
<td>41:37:50.4</td>
<td>22.3±0.2</td>
<td>63.3±0.3</td>
<td>27.5±1.2</td>
<td>0.82</td>
<td>3.03</td>
<td>20.4±22.9</td>
<td>0.6</td>
</tr>
<tr>
<td>MEGA-ML 9</td>
<td>0:44:46.80</td>
<td>41:41:06.7</td>
<td>21.97±0.08</td>
<td>391.9±0.1</td>
<td>2.3±0.4</td>
<td>1.02</td>
<td>2.49</td>
<td>0.9±0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>MEGA-ML 10</td>
<td>0:43:54.87</td>
<td>41:10:33.3</td>
<td>22.2±0.1</td>
<td>75.9±0.4</td>
<td>44.7±5.6</td>
<td>1.28</td>
<td>5.88</td>
<td>1.4±0.5</td>
<td>1.1</td>
</tr>
<tr>
<td>MEGA-ML 11</td>
<td>0:42:29.90</td>
<td>40:53:45.6</td>
<td>20.72±0.03</td>
<td>488.43±0.04</td>
<td>2.3±0.3</td>
<td>1.03</td>
<td>13.27</td>
<td>1.5±0.4</td>
<td>0.2</td>
</tr>
<tr>
<td>MEGA-ML 13</td>
<td>0:43:02.49</td>
<td>40:45:09.2</td>
<td>23.3±0.1</td>
<td>41.0±0.3</td>
<td>26.8±1.5</td>
<td>0.75</td>
<td>1.68</td>
<td>9.2±10.8</td>
<td>0.8</td>
</tr>
<tr>
<td>MEGA-ML 14</td>
<td>0:43:42.53</td>
<td>40:22:33.9</td>
<td>22.5±0.1</td>
<td>455.9±0.1</td>
<td>25.4±0.4</td>
<td>1.11</td>
<td>3.74</td>
<td>146±182</td>
<td>0.4</td>
</tr>
<tr>
<td>MEGA-ML 15</td>
<td>0:43:09.28</td>
<td>41:20:53.4</td>
<td>21.63±0.08</td>
<td>1145.5±0.1</td>
<td>16.1±1.1</td>
<td>1.23</td>
<td>4.41</td>
<td>7.0±2.2</td>
<td>0.5</td>
</tr>
<tr>
<td>MEGA-ML 16</td>
<td>0:42:51.22</td>
<td>41:23:55.3</td>
<td>21.16±0.06</td>
<td>13.38±0.02</td>
<td>1.4±0.1</td>
<td>0.93</td>
<td>2.81</td>
<td>2.6±0.7</td>
<td></td>
</tr>
<tr>
<td>MEGA-ML 17</td>
<td>0:41:55.60</td>
<td>40:56:20.0</td>
<td>22.2±0.1</td>
<td>1160.7±0.2</td>
<td>10.1±2.6</td>
<td>0.79</td>
<td>2.02</td>
<td>0.5±0.3</td>
<td>0.4</td>
</tr>
<tr>
<td>MEGA-ML 18</td>
<td>0:43:17.27</td>
<td>41:02:13.7</td>
<td>22.7±0.1</td>
<td>1143.9±0.4</td>
<td>33.4±2.3</td>
<td>1.13</td>
<td>1.83</td>
<td>13.7±16.3</td>
<td>0.5</td>
</tr>
</tbody>
</table>
10 and 15 have a somewhat high $\chi^2$, but are located in high surface brightness regions. Only event 7 has a high $\chi^2$, but since $\Delta \chi^2/N$ is high, it easily satisfies our selection criteria.

All candidate events are consistent with achromaticity, although for low signal-to-noise events, it is difficult to draw firm conclusions from the lightcurves or $\Delta r'$ versus $\Delta i'$ plots. None of the events is ruled out by either the colour evolution or the KP4m data. In a lot of cases, some fit parameters have large uncertainties, due to the degeneracies between the unlensed flux $F_0$, impact parameter $\beta$ and timescale $t_{FWHM}$. However, the values found for the unlensed $r'$ flux $F_{0,r}$ and $r'$-$i'$ colour, listed in table 5.3, still give some indication of the properties of the source stars. The unlensed fluxes are consistent with the range that we expect, roughly from 0.1 to 10 ADU s$^{-1}$ (see figure 5.2). Also the colours of the majority of the events lie within the typical range for red giant stars.

Dividing the events by season, we have seven events in the first season, four in the second season, none in the third season and three in the fourth season. That more events are detected in the first two seasons is not surprising, as the amount of data available is larger (see table 5.1) because of a lot of bad weather in the third and fourth season. The many gaps in the time coverage in the last two seasons conspired particularly against short events and the events detected in the fourth season are all of moderately long duration.
5.5. Microlensing event sample

Figure 5.6 – Detail of two KP4m difference images centered on the position of event 3. Left: October 27th 1997, almost 3 years before the event peaks, a very faint residual is seen centered just 1 pixel (0.21") away from the event. Right: September 26th 2000, during the peak of the event that is displaced from the position of the faint variable.

5.5.2 Comparison with other surveys

Since the POINT-AGAPE collaboration uses the same INT data set for their M31 microlensing survey as this study, it is interesting to compare our microlensing sample with the events reported by them. Paulin-Henriksson et al. (2003) performed a search for short ($t_{\text{FWHM}} < 25$ days) duration, high signal-to-noise microlensing events in the first two observing seasons that resulted in four convincing events. They argued that one of these events (PA-00-S3) is probably due to a stellar lens in the M31 bulge. This event lies in the region of the bulge excluded from our analysis (see figure 5.1). The other three events, PA-99-N1, PA-99-N2, and PA-00-S4 correspond to our events 15, 7, and 11. We find in the first two observing seasons a total of eleven events, so the remaining eight events evidently do not satisfy their rather severe selection criteria.

In Belokurov et al. (2005) the POINT-AGAPE collaboration analysed the first three INT observing seasons, without restrictions on the event duration. They found three high quality candidates. One of these was not previously detected, one corresponds to our event 11, or PA-00-S4, and one corresponds to PA-00-S3. The new event is present in our survey, but does not pass our selection criteria because of a high $\chi^2$. In figure 5.7 we show our lightcurves of this candidate microlensing event. Our best-fit standard microlensing model is also plotted, but clearly cannot reproduce the observed lightcurve behaviour very well. The peak appears to be asymmetric about the peak time $t_{\text{max}}$; the $i'$ data are systematically below the model around 15 days prior to $t_{\text{max}}$ and systematically above the model around 15 days after $t_{\text{max}}$. Since there are no data available at all on the rising part of the peak, $t_{\text{max}}$ is poorly constrained and it is possible that the actual peak in the flux occurs earlier than at the fitted $t_{\text{max}}$. When comparing our lightcurves to the ones presented by Belokurov et al. (2005), the $r'$ peaks have the same shape, although Belokurov et al. (2005) have removed one epoch close to the peak center that is present in our lightcurve. In the $i'$ lightcurves the peak shape differs somewhat.

Peak asymmetries can be caused by secondary effects like parallax effects, but the peak shape that seems inconsistent with microlensing together with the high brightness of the peak suggest this might actually be a nova-like eruptive variable. The event appears to be achromatic, but the colour of classical novae can remain constant as well on the declining part of the lightcurve, see for example figure 4.19 in this thesis or Darnley et al. (2004). If this is a classical nova, it would be a very fast one, with a decline rate corresponding to $\sim 0.6$ mag per day. Overall, we question the microlensing nature of this candidate event.

Calchi Novati et al. (2005) found six candidate microlensing events in another analysis of the three-year INT data set. Of these, four are the same as reported by Paulin-Henriksson
et al. (2003) and two are new events: PA-00-N6 and PA-99-S7. The latter is located in the bright part of the southern field excluded in our analysis (see figure 5.1). Candidate event PA-00-N6 is present in our data, but was only detected in one epoch in our automatic SExtractor

Figure 5.7 – Our photometry for microlensing event candidate 1 from Belokurov et al. (2005).
5.6 Detection efficiency

Since the selection procedure described in section 5.4 is completely automated and reproducible, we can use the Monte Carlo simulations discussed in section 5.3 to determine our detection efficiency for microlensing events. Simulated lightcurves are generated by adding artificial events to the difference images and analysing them with the same pipeline used for the actual data. Applying the selection criteria for microlensing yields a catalogue of simulated detected microlensing events. The detection efficiency is the ratio of this number of detected events to the original number of artificial events.

In the simulations we use discrete values of intrinsic source flux, to determine the microlensing detection efficiency for different source populations. We first check that the sampled range of source fluxes covers the portion of the source luminosity function responsible for most of the detectable events. The function \( N_s \beta_u^2 \) in figure 5.2 is meant to give a qualitative picture of the detectability of microlensing as a function of source luminosity. Here we consider the function \( P_{\text{det}} \equiv N_s \beta_u^2 \epsilon \) where \( \epsilon \) is the detection efficiency as a function of \( F_{0,r} \) integrated over \( \beta \), \( t_{\text{FWHM}} \) and position. \( P_{\text{det}} \) gives the relative probability for detection of a microlensing event as a function of the source luminosity for our specific survey and analysis setup. As shown in figure 5.8, the range 0.01 to 10 ADU s\(^{-1}\) adequately covers the peak of this probability distribution, meaning that the simulated events are representative of the events that we are most sensitive to.

In figure 5.9 the detection efficiencies are plotted for two regions as function of the impact parameter \( \beta \) for four different values of \( t_{\text{FWHM}} \) for the brightest and the faintest source stars. As expected, the detection efficiency generally increases for increasing \( t_{\text{FWHM}} \), and for smaller \( \beta \). However, for \( F(r) = 10 \text{ADU s}^{-1} \), there is a dip at small \( \beta \) when \( t_{\text{FWHM}} > 10 \). This problem is probably caused by the underestimation of the photometric error at high residual detection step and therefore did not make it into the catalogue of variable sources. Calchi Novati et al. (2005) do not detect our events 1, 2, 3, 8, 9, 10, 13, and 14, all peaking in the first two observing seasons. Evidently, these events do not satisfy their signal-to-noise constraints.

Figure 5.8 – Relative probability of detecting a microlensing event of a source star with a certain intrinsic flux. This probability is the product of the number of available stars (taken from the luminosity function), the square of the maximum impact parameter for which an event can be detected, and the detection efficiency for each source population, averaged over all \( t_{\text{FWHM}} \). The figure shows that our range of simulated source fluxes from 0.01 to 10 ADU s\(^{-1}\) covers the peak of the distribution very well.
Figure 5.9 – Detection efficiencies as function of impact parameter $\beta$ for different values of $t_{\text{FWHM}}$ (50, 10, 3 and 1 days). The two upper panels show the fraction of simulated events that pass the microlensing selection criteria for 2 source fluxes, 10 and 0.01 ADU s$^{-1}$, in the south-east chip of the north field. The lower panels show the same for the south-east chip of the south field.

Our goal is to describe the detection efficiency with a functional form that depends on a few parameters. The dominant parameters that influence the probability a microlensing event is detected are its duration and peak brightness. Therefore, it should be possible to express the detection efficiency as a function of $t_{\text{FWHM}}$ and $\Delta F_{\text{max}}$. Since the shape of the standard microlensing lightcurve does not depend strongly on $\beta$ (e.g. figure 3.2), we expect that there is no significant dependence on the intrinsic source brightness $F_{0,r}$. In figure 5.10 we plot the detection efficiencies for events with $t_{\text{FWHM}}=50$ days as a function of $1/\Delta F_{\text{max}}$ for

fluxes, because of which the $\chi^2$ of the microlensing fits are systematically too high for events with many high flux points. The detection efficiency is higher for $t_{\text{FWHM}}$ of 10 than 50 days, because long duration events have an increasing chance that their peaks do not lie entirely within one observing season.
Figure 5.10 – Detection efficiencies as a function of $1/\Delta F_{\text{max}}$ for $t_{\text{FWHM}}=50$ days and $F_{0,\text{r}} = 10$ ADU s$^{-1}$ (solid line), 1 ADU s$^{-1}$ (dotted line), 0.1 ADU s$^{-1}$ (long-dashed), and 0.01 ADU s$^{-1}$ (short-dashed line). In general the lines overlap within the errors.

Four different regions. The curves overlap within the error bars, indicating that the detection efficiency indeed depends on the peak brightness and that $\beta$ and $F_{0,\text{r}}$ are highly degenerate.

Another property of microlensing events that could affect the detection efficiency is their colour, even though there is no explicit colour cut in our selection procedure. All simulated events have a colour of $r'-i'$, but in part of the north field we also ran simulations with events 0.5 magnitude redder, keeping $r'$ constant. Figure 5.11 compares the detection efficiencies for the two colours and shows that there is no significant colour dependence. Only for the very highest signal-to-noise events there is a difference. This is caused by the problem with the photometric error estimates discussed above that causes a decrease in detection efficiency for high signal-to-noise events. For the redder events this is enhanced because the sources have a higher intrinsic $i'$-band flux. Since this affects only very few events, we conclude that the influence of colour on the detection efficiency can be neglected.
Having established that $t_{\text{FWHM}}$ and $\Delta F_{\text{max}}$ are indeed sufficient to describe the detection efficiency, we have to find an appropriate functional form. Based on the shapes of the curves, as seen in figure 5.11, we choose a Gaussian in $1/\Delta F_{\text{max}}$ with a peak position that depends on $t_{\text{FWHM}}$. The exact functional form is given by:

$$e = c_1 \cdot e^{-c_2(\frac{1}{\Delta F_{\text{max}}}-c_3)^2} \cdot \frac{448 - 4 \cdot t_{\text{FWHM}}}{448},$$

(5.9)

where $c_3 = d_1 \cdot \ln(t_{\text{FWHM}}) + d_2$. (5.10)

The last term in equation 5.9 scales the Gaussian down for long events, to take into account that the detection efficiency decreases sharply for long duration events due to the limited length of the observing seasons. The parameters $c_1$, $c_2$, $d_1$, and $d_2$ are determined by fitting simultaneously the detection efficiencies for all values of $t_{\text{FWHM}}$. Figure 5.12 shows an example for one chip of these fits to the detection efficiencies.

From figure 5.10 it is apparent that the detection efficiencies also depend on location in the field. This is mainly due to the changing galaxy surface brightness, but also due to bad pixels and saturated star defects. To account for the spatial variation each chip is divided in 32 subregions of $\sim 3' \times 3'$ size. For each of these regions we have on average 14 640 simulated events (2 440 per $t_{\text{FWHM}}$). The spatially varying microlensing detection efficiency is obtained by fitting the four parameters in equation 5.9 in each $3' \times 3'$ region in the INT fields.

### 5.7 Extinction model

That compact objects in the halo of M31 would reveal their presence by inducing a near-far asymmetry in the microlensing event distribution, is one of the main motivations for the microlensing surveys toward M31. In the absence of significant intrinsic asymmetries in
5.7. Extinction model

Figure 5.12 – Detection efficiencies as a function of $1/\Delta F_{\text{max}}$ for different values of $t_{\text{FWHM}}$. The symbols give the results of the Monte Carlo calculation for one chip. The lines correspond to the fitting formula, equation 5.9.

M31, the distribution of self-lensing events and variable stars masquerading as microlensing events would be symmetric. The detection of a near-far asymmetry in the microlensing event distribution would then be evidence for the presence of a significant MACHO population.

However, as was shown by An et al. (2004a) and also in chapter 4 of this thesis, a similar asymmetry is present in the distribution of the variable stars in M31, caused by variable extinction within M31. In order to account for this in our models, we construct a first-order extinction model to test how extinction influences our theoretical predictions of the microlensing rate and distribution.

M31 shows several prominent dust features of which two dust lanes are most obviously visible on the near side of the disk. How the dust is distributed perpendicular to the plane of the disk is, however, unknown. Following the approach of Walterbos & Kennicutt (1988) we assume that the dust is located in an infinitely thin layer in the midplane of the disk. For every line-of-sight, the light emitted in front of the midplane is then completely unextincted, while the light emitted behind the midplane is partly absorbed, depending on the local optical depth of the dust layer. This simplifying assumption can be used to show why the extinction poses more of a problem on the near side of M31 than on the far side. Because of the high inclination of M31 the fraction of stars located behind the midplane of the galaxy is higher on the near side, as illustrated in figure 5.13. Therefore, even if the distribution of the dust is symmetric, the effect of extinction will be much stronger on the near side of the disk.

Based on this assumption the observed intensity along a certain line-of-sight can be written as

$$I_{\text{obs}} = I_{\text{front}} + I_{\text{back}} \cdot e^{-\tau}$$  \hspace{1cm} (5.11)

where $I_{\text{front}}$ ($I_{\text{back}}$) is the intensity of light originating from in front of (behind) the dust layer and $\tau$ is the optical depth. If we make a model of the fraction $x$ of the light (before extinction) that originates in front of the dust layer as a function of position, then for each
Figure 5.13 – Schematic representation of the line-of-sight through the M31 galaxy from an observer on earth. Because of the high inclination of M31, most of the light observed on the near side of the disk is coming from behind the dust lanes.

Table 5.4 – Disk and bulge parameters used to derive $x$, the fraction of light originating in front of the midplane of M31: the scalelength and scaleheight, $h_l$ and $h_z$, for disk and bulge, and the fraction of the total light coming from the bulge.

<table>
<thead>
<tr>
<th></th>
<th>Disk</th>
<th>Bulge</th>
<th>$L_b/(L_b + L_d)$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$h_l$ (kpc)</td>
<td>$h_z$ (kpc)</td>
<td>$h_l$ (kpc)</td>
</tr>
<tr>
<td>B</td>
<td>5.8</td>
<td>0.3</td>
<td>1.2</td>
</tr>
<tr>
<td>I</td>
<td>5.0</td>
<td>0.7</td>
<td>1.2</td>
</tr>
</tbody>
</table>

For determining the fraction $x$ of light originating in front of the midplane, we model both the disk and the bulge of M31 as a double exponential. Since most of the B-band flux is produced by young stars, which have a different spatial distribution than the older stellar populations, we use different models for $x$ for these two bands. To construct these models we use the parameters listed in table 5.4. The values of the disk scale lengths and the bulge-to-disk-ratios are taken from Walterbos & Kennicutt (1988). The scale length and height of the
5.7. Extinction model

Figure 5.14 – Extinction map in the I-band for the observed INT fields, calculated using the method described in this section. Only in a few small patches more than 40% of the flux is removed. Extinction is clearly more severe on the near side of the galaxy than on the far side.

bulge are adapted from their de Vaucouleurs fit to the bulge. The disk scale heights are based on the distribution of different stellar populations in the Milky Way disk. In equation 5.14 we then use the $x$ model for B-band, while we use the model for I-band to correct the observed I-band flux. For the B- and I-band fluxes we use observations made by Guhathakurta et al. (2004) of a $1.7^\circ \times 5^\circ$ field centered on M31, with effective exposure times of 20 minutes in B and 40 minutes in I. We also use these mosaics to estimate the intrinsic colour profile and find a colour profile as a function of radius that behaves similarly to the colour profiles found by Walterbos & Kennicutt (1988), with almost constant colour within a radius of $30''$ and getting bluer at larger radii.

Following the recipe described above we derive an extinction map of M31. The I-band extinction map for our fields is shown in figure 5.14. The major dust lanes are clearly seen in the near side part of the northern field. As expected the extinction is much larger on the near
side of the galaxy than on the far side. The I-band attenuation reaches a maximum of 40% in the innermost dust lane and a few smaller complexes. Although this extinction map should be considered as a first-order guess, it successfully reproduces large-scale patterns such as the dust lanes and most other complexes. However, this method has some intrinsic caveats.

The method is only sensitive if a large fraction of the light originates behind the dust layer. At the far side of M31, where most of the light originates in front of the dust, the effect of extinction is negligible, resulting in a $\tau = 0$ dust layer in our extinction map. This asymmetry in the extinction map does not reflect an asymmetry in the dust distribution, but rather an asymmetry in the effect that the dust has on the observed flux. This is not a concern for our purposes, since we are interested in the severity of the extinction, not in the dust layer itself.

But also on the near side the method almost certainly underestimates the effect of extinction. The method relies on comparing the observed flux ratio $I_{\text{obs}}(B)/I_{\text{obs}}(I)$ with the intrinsic colour $C_{HI}$, which means that it will fail in the case of grey extinction. For very high extinction, $\tau \gg 1$, the approximation $I_{\text{obs}}(I) \approx I_{\text{int}}(I)$ is not valid. If most of the light behind the dust is absorbed, the observed flux is dominated by the light originating in front of the dust. The observed colour will be the intrinsic colour, and equation 5.14 will give $\tau = 0$. Therefore, in highly extinguished regions like the centers of the dust lanes, the extinction is likely to be underestimated. Also if the dust is distributed in optically thick clumps with optically thin regions in between, I and B fluxes will be absorbed in equal amounts. Moreover, the assumption that the dust is in an infinitely thin layer decreases the obtained extinction values, as argued by Walterbos & Kennicutt (1988). Finally, scattering by the dust increases the observed flux and therefore also leads to an underestimate of the extinction.

Walterbos & Kennicutt (1988) do a similar analysis along the dust lanes on the near side of M31 and find R-band extinctions of typically a few tenths of a magnitude, going up to about 1 magnitude in a few places, in good correspondence with our extinction model. They also emphasize that these values are lower limits due to the limitations of the method.

The variable stars in our survey can be used to test and perhaps improve our extinction map. We assume that the variable stars are distributed symmetrically over M31. Of all variable stars, long-period variables (LPVs) are best suited for this test because they generally belong to quite old stellar populations and are therefore more smoothly distributed over the galaxy than younger variable stars, such as Cepheids. We select LPVs with periods between 150 and 650 days and that are well-fit by a Fourier series (equation 4.1). (These are the same LPVs that were discussed in section 4.3.3.) Here we focus on two regions in our INT fields that are located symmetrically with respect to the center of M31. One of the regions is located on the heavily extincted near side of the disk, the other one on the almost unaffected far side. Figure 5.15 shows the spatial distribution of the LPVs as well as the two regions. The amplitudes of the LPVs can tell us something about the mean extinction in these two regions. If an LPV is extincted, the amplitude of the flux variation will be affected the same way as the average flux. Assuming that there are no intrinsic differences between the LPV populations in the two regions, we should see the effect of extinction by comparing the distribution of the LPV amplitudes in the two regions.

Following An et al. (2004a) in their abuse of the terminology, we will also refer to the amplitude distributions as luminosity functions. Figure 5.16 compares the LPV luminosity functions (LFs) of the LPVs located in the near side and far side field. On the faint side, that is determined by the detection efficiency, the two LFs overlap. However, on the bright side there is a large offset. On the bright end of the LFs completeness should be 100% and if the
intrinsic distribution of LPVs in M31 is homogeneous and symmetric, the LFs are expected to overlap. This is clearly not the case, and this is explained by a large fraction of the near side LPVs being extincted, systematically lowering their observed amplitudes and thereby shifting the LF toward fainter amplitudes.

To test the extinction model we will use it to extinct the LPVs in the far side region to see if we can reproduce the near side LF. This is done by transforming the coordinates of the LPVs from the far to the near side region by mirroring them through the center of M31 and extincting an appropriate fraction of them according to the extinction values from our extinction model. Since we use r' amplitudes, the I-band extinction values in figure 5.14 are transformed to r'-band values following the standard extinction law (Savage & Mathis 1979). The resulting, extincted far side LF is shown in figure 5.16 with the short-dashed line. Although the extincted LF is closer to the near side LF, it is still significantly brighter, suggesting that our extinction model underestimates the actual effect of extinction. An easy way to increase the extinction in the model that also increases it more strongly in heavily extincted regions is to simply multiply the optical depth $\tau$ with a constant. Also plotted in figure 5.16 are the LFs of the far side LPVs for increased extinction models: the long-dashed line is for a model with $2\tau$, the dot-dashed line for a model with $2.5\tau$. By multiplying the optical depths of our extinction model by 2.5, the bright side of the extincted far side LF transforms to overlap very well with the bright side of the near side LF.

This comparison of the LPV amplitudes indicates that the extinction model does indeed underestimate the extinction. An increase of the model $\tau$ with a factor 2.5 does well to explain the difference in the LPV luminosity functions between the near and far side. Our original extinction map will underestimate the actual extinction more strongly in some places than in others. Over the probed region the model seems to underestimate the extinction effectively by a factor 2.5 in $\tau$. 

Figure 5.15 – The two symmetrically placed regions used for the LPV amplitude analysis. The northern field is located on the near side and contains some of the most heavily extincted parts, the southern field is on the far side and hardly affected by extinction. These regions are similar to N2 and S2 regions from An et al. (2004a), only adjusted to avoid the part of the southern INT field that is not used in our analysis.
5.8 Theoretical predictions

With the microlensing detection efficiencies and an extinction model in hand, we can use specific galaxy models to make predictions for the microlensing event rate and distribution. Comparing the sample of observed candidate events to these theoretical predictions will allow us to constrain the amount of MACHOs in the M31 halo. In this section we describe theoretical calculations of the expected number of microlensing events and their distribution for this survey. First, the models of M31 we use are discussed in subsection 5.8.1. The details of the microlensing event rate calculations are described in subsection 5.8.2. In subsection 5.8.3 the results of the theoretical calculations are presented.

5.8.1 Self-consistent models of M31

To model M31 we use the axisymmetric, self-consistent galaxy models developed by Widrow & Dubinski (2005), following the approach of Kuijken & Dubinski (1995). We will not use exactly the same models of M31 constructed in Widrow & Dubinski (2005), but versions of these that are adapted for our needs. These models are derived from explicit distributions functions (DFs) for three components: a disk, a bulge, and a dark halo. The central black hole is left out of our models as its influence on the microlensing results is negligible. For the exponential disk, the disk DFs from the models by Kuijken & Dubinski (1995) are used. The bulge is modeled using the Hernquist model (Hernquist 1990). The dark halo is modeled to follow the density profile found by Navarro et al. (1996), the so-called NFW profile. Each component is described by several parameters and in total the models have 15 free parameters. Using the DFs for the different components, the gravitational potential is varied iteratively until a self-consistent composite disk-bulge-halo model is achieved.

The models constructed this way can be fit to a wide range observational data. For a comparison with photometric data, mass-to-light ratios must be specified. From the models, N-
body representations can be generated that can be “observed” to derive model surface brightness profiles, rotation curves and velocity dispersions. Comparing these pseudo-observations to real data allows one to find a best-fit model. The observational data we use to constrain our M31 models include the minor and major axes surface brightness profiles from Walterbos & Kennicutt (1988) and a combined rotation curve from the observations of Kent (1989) and Braun (1991) that runs from 2 to 25 kpc in galactocentric radius. Stellar rotation and velocity dispersion measurements from McElroy (1983) are used to constrain the dynamics in the innermost part of the galaxy. Comparing pseudo-observations of the model surface brightness profile, rotation curve and bulge dynamics to the observations, yields an individual $\chi^2$ for each of these. We give equal weight to the photometric and kinematic data, but the rotation curve is weighted more heavily than the bulge dynamics. The composite $\chi^2$ is given by

$$\chi^2 = \frac{1}{\sqrt{2}} \sqrt{\chi_{SBP}^2 + \frac{2}{3} \chi_{RC}^2 + \frac{1}{3} \chi_B^2}$$

where $\chi_{SBP}^2$, $\chi_{RC}^2$, and $\chi_B^2$ are for the surface brightness profile, rotation curve and bulge dynamics. To search the vast parameter space for the best-fitting model, the downhill simplex algorithm (see e.g. Press et al. 1992) is used.

A whole suite of models gives acceptable fits to the observations. Therefore we want to use some priors on the $M/L$ and the vertical scaleheight of the disk. Reasonable values for the disk and bulge $M/L$ are obtained using the stellar population models by Bell & de Jong (2001) together with colour information from Walterbos & Kennicutt (1988). From the far-side minor axis surface brightness profile, that should be almost free from internal extinction, we get a bulge colour of $B-R \approx 1.75$ and for the disk $B-R \approx 1.55$. Using foreground reddening calculated from Schlegel et al. (1998) of $E(B-R)=0.1$ and a small correction for internal extinction, this yields $M/L$ values between 3.4 and 3.8 for the bulge and between 2.2 and 2.6 for the disk.

The vertical scale height of the disk of M31 is poorly known, but will have significant impact on the microlensing rate through the self-lensing within the disk. Kregel et al. (2002) find for a sample of edge-on galaxies that the average ratio between exponential scale length and scale height of the disks is 7.3, with considerable scatter. Since the R-band scale length is quite well constrained at 5.5 kpc, a scale height of 0.7±0.2 seems reasonable. The result of Kregel et al. (2002) was obtained from I-band data, and for R-band a slightly lower scale height can be expected. Because the disk DF in our models uses a $\text{sech}^2(z)$ vertical distribution, we have to convert the exponential scale heights to the $\text{sech}^2$ equivalent.

For our default model we choose to use $(M/L)_{\text{bulge}}=3.6$, $(M/L)_{\text{disk}}=2.4$, and a $\text{sech}^2$ scale height $h_z$ of 1.0 kpc, which corresponds to an exponential scale height of about 0.5-0.7 kpc. The disk truncation radius is also fixed at 28 kpc, which is at the high end of the range favoured by Kregel et al. (2002). Lower values seem to be inconsistent with the measured surface brightness profile. The remaining parameters for the disk, bulge, and halo DFs are varied in order to minimize $\chi^2$. In figure 5.17 the model surface brightness profile and rotation curve of this model A1 are compared to the observational data, showing excellent agreement. The $\chi^2$ of this model is 1.06. Table 5.5 shows all the models we consider. Models B1-E1 explore the $(M/L)_{\text{bulge}}$ and $(M/L)_{\text{disk}}$ plane. All models have quite a low $\chi^2$, because of a degeneracy between luminous and dark mass; bulge and disk mass are traded off against halo mass. In models F1 the scale height is halved and models G1 and H1 are variations of the assumed MACHO mass.
Figure 5.17 – Comparison of pseudo-observations of model A1 to real observations. *Upper panel:* model surface brightness profiles (solid lines) along the major and minor axis compared to observations by Walterbos & Kennicutt (1988) (dots). For clarity the profiles are shifted down in steps of 2 magnitudes. From the top down the profiles correspond to: SW major axis, NE major axis, SE minor axis (near side), and NW minor axis (far side). *Lower panel:* model rotation curve (solid line) and combined rotation curve from Kent (1989) and Braun (1991). Also indicated are the contributions to the rotation curve of the bulge (dotted line), disk (long-dashed line), and halo (short-dashed line).

The models include extinction, using the extinction map derived in section 5.7. This is done by correcting the observed SBPs for extinction and comparing the model SBPs with these extinction-corrected observations. However, as discussed there, the extinction map is likely to be an underestimate. In fact, the analysis of the amplitudes of the LPVs on the far and near side of M31 favours an optical depth that is 2.5 times higher. For this reason we also consider a parallel sequence of models A2-H2 with this higher extinction value. The $\chi^2$ values of these models are even slightly better than those for the low-extinction models.

### 5.8.2 Event rate calculation

The self-consistent galaxy models of M31 are used to calculate predicted event rates for our survey. Below we describe how one goes from the DFs that define the galaxy model to the expected number of microlensing events and their spatial distribution.

*Event rates from distribution functions*

As an example, we first consider a simple case where all lenses have the same mass $M_l$ and all sources have the same luminosity $L_s$. The density and velocity distribution of a galaxy component along the LOS is given by its DF $f(l, v)$, where $l$ is the distance along the LOS. For a single source in M31 the rate at which lenses pass in front of the source is given by

$$dR = \int \frac{f_l(l, v_l)}{M_l} 2R_Ev_\perp dl_l dv_l d\beta$$  \hspace{1cm} (5.16)$$

where $f_l$ is the DF for the lenses, $l_l$ is the observer-lens distance, $R_E$ is the Einstein radius (equation 5.2), $v_\perp$ is the transverse velocity of the lens with respect to the observer-source.
line-of-sight, and $\beta$ is the impact parameter in units of the Einstein radius. Going from one source to a distribution of sources described by the DF $f_s$, we get the following expression for the rate per unit solid angle:

$$\frac{dR}{d\Omega} = \int f_l(l_i, v_i) \frac{f_s(l_s, v_s)}{M_l (M/L)_s L_s} \ 2R_{E\perp} v_{\perp} \ dl_i dv_i \ l_s^2 \ dl_s dv_s \ d\beta$$  \hspace{1cm} (5.17)

where $l_s$ is the observer-source distance. Of course, $l_i$ should be integrated up to $l_s$ since the lenses have to be in between the observer and the source.

In order to create microlensing events, the DFs along the line-of-sight can be represented as a set of randomly selected particles with the appropriate space and velocity distribution:

$$f_l(l_i, v_i) = \frac{\Sigma_l}{N_l} \sum_{i=1}^{N_l} \delta(l_i - l_i) \ \delta(v_l - v_i)$$  \hspace{1cm} (5.18)

$$f_s(l_s, v_s) = \frac{\Sigma_s}{N_s} \sum_{j=1}^{N_s} \delta(l_s - l_j) \ \delta(v_s - v_j)$$  \hspace{1cm} (5.19)

where $\Sigma_l$ and $\Sigma_s$ are the surface mass densities of the lenses and sources along the line-of-sight respectively. Now the integrals over $l$ and $v$ in equation 5.17 become sums:

$$\frac{dR}{d\Omega} = S_{st} \sum_{i,j} \int_{0}^{\beta_0} d\beta R_{ij},$$  \hspace{1cm} (5.20)

where $S_{st} = \frac{\Sigma_l \Sigma_s}{N_l M_l N_s (M/L)_s L_s}$, \hspace{1cm} (5.21)

and $R_{ij} = (2R_{E\perp})_{ij} l_{s,j}^2$ \hspace{1cm} (5.22)

The sum is restricted to all lens-source pairs for which the lens is located between the observer and the source. Note that $S$ depends on the line-of-sight densities of the lens and source populations as well as on the characteristics of the populations. $R_{ij}$ depends on the velocities and characteristics of the lens and source of each lens-source pair (hence the $ij$ subscript). For each lens-source pair the velocities and distances are known and the Einstein crossing time, $t_{E,ij}$ can be calculated, so that we also know the event rate as a function of $t_E$:

$$\frac{d^2R}{d\Omega dt_E} = S_{st} \sum_{i,j} \int_{0}^{\beta_0} d\beta R_{ij} \delta(t_{E,ij} - t_E)$$  \hspace{1cm} (5.23)

Stellar and MACHO populations

The formulae discussed above apply to the six combinations of lens-source populations in our models: disk-disk, disk-bulge, bulge-disk, bulge-bulge, halo-disk, and halo-bulge. However, above we assumed the same mass for all lenses and the same luminosity for all sources. For our theoretical predictions equation 5.20 is modified to include integrals over realistic mass and luminosity functions for the disk and bulge populations. We write the luminosity function (LF) as

$$\frac{dN}{dM_R} = A g(M_R)$$  \hspace{1cm} (5.24)
and the mass function (MF) as
\[
\frac{dN}{d\mathcal{M}} = B h(\mathcal{M}, \mathcal{M}_0)
\]  
(5.25)

where \(A\) and \(B\) are normalization constants and \(\mathcal{M}_0\) is the lower bound for the mass function. For both disk and bulge we use the R-band luminosity function from Mamon & Soneira (1982) for \(\varphi\). For the function \(h\) we use a MF from Binney & Merrifield (1998) (their equation 5.16) with the power-law form \(dN/DM \propto M^{-1.8}\) extended to \(\mathcal{M}_0\). \(A\) and \(B\) are evaluated separately for the disk and the bulge. In the case of the disk we assume that 30% of the mass is in the form of gas. The LF is normalized to give \(L = L_\odot\), which leaves us to determine \(B\). We can write
\[
B h(\mathcal{M}_\odot, \mathcal{M}_0) = \left( \frac{dM_V}{d\mathcal{M}} \frac{dN}{dM_V} \right)_{\mathcal{M}=\mathcal{M}_0}
\]  
(5.26)

where \(dM_V/dm\) is from Kroupa et al. (1993) and the V-band LF from Mamon & Soneira (1982), and evaluate this equation at solar values for convenience. Then we can determine \(\mathcal{M}_0\) by requiring that:
\[
\left( \frac{M}{L} \right)_R = \int B h(\mathcal{M}, \mathcal{M}_0) \mathcal{M} d\mathcal{M} \int A g(\mathcal{M}_R) L(\mathcal{M}_R) d\mathcal{M}_R
\]  
(5.27)

and solve for \(\mathcal{M}_0\). Thus, the lower limit on the MF is determined by the \(M/L\), so that a high \(M/L\) disk contains more low-mass stars than a disk with low \(M/L\).

The nature and mass of possible MACHOs is unknown. For simplicity we use for the MACHO component a single mass, \(\mathcal{M}_{\text{macho}}\), for all MACHOs.

**Theoretical prediction of microlensing events**

Inserting the LF and MF into equation 5.20 yields an expression for the event rate per unit solid angle. In section 5.6 we described how the detection efficiency for microlensing events is derived in \(3' \times 3'\) subregions, resulting in 250 spatial bins over the analysed field. To get the expected number of events for our survey, we need to calculate the event rate for each of these spatial bins. The detection efficiency \(\epsilon\) is described as a function of \(t_{\text{FWHM}}\) and \(\Delta F_{\text{max}}\). For every lens-source pair these are known, so that \(\epsilon\) can be easily included. Thus, we get the following expression for expected number of events in the \(k\)-th spatial bin:
\[
\mathcal{E}_k = \Delta \Omega E A B S t_s \sum_{i,j} \int_{0}^{\beta_0} d\beta \int dM_R g(M_R) 
\times \int d\mathcal{M} h(\mathcal{M}, \mathcal{M}_0) \mathcal{R}_{ij} \epsilon(t_{\text{FWHM}}, \Delta F_{\text{max}})
\]  
(5.28)

where \(E\) is the overall duration of the experiment (four 6-month observing seasons, or two years), and \(\Delta \Omega = 9\) arcmin\(^2\) is the angular area of the bin. The total number of events is of course \(\mathcal{E} = \sum \mathcal{E}_k\).

We use an integration limit \(\beta_0 = 2\), since even for very bright stars, events with \(\beta > 2\) are too faint to be detected (see table 5.2). However, not all lens-source pairs will in reality have an impact parameter smaller than \(2R_E\). Therefore, an extra correction factor of \(\pi(2R_{E,ij})^2\) is inserted in equation 5.28.
Some of the events will be extincted and therefore have a lower $\Delta F_{\text{max}}$. The extinction model (either the original map derived in section 5.7, or the high extinction version) is used to take this into account. For this purpose, the extinction map is resampled so that there are 25 resolution elements in each spatial bin. Then, for all events that have a source star located behind the midplane of the galaxy, one of the 25 extinction values is randomly chosen and the event is extincted accordingly.

**Binary lenses**

Our microlensing selection procedure is specifically designed to look for standard microlensing events: the case of a single point-like lens gravitationally lensing a single point-like background source. Also in the theoretical calculations all events are treated as standard events. However, at least half of all stars are part of a binary or multiple star system. The lightcurves of microlensing events in which the lens is made up of two point masses can deviate strongly from standard microlensing (Schneider & Weiss 1986) lightcurves. A fraction of self-lensing events in M31 might not satisfy our microlensing selection criteria because of this. Microlensing events with a binary lens will show very strong deviations from the standard lightcurve if the source crosses the so-called caustics, the positions in the lens plane where the magnification is theoretically infinite. If the source does not pass the caustics, the lightcurve is much less deformed, depending on how close it approaches them. The size of the caustic region depends on the mass ratio of the lens components, their separation and the total mass of the system; the size of the caustic region peaks when the separation of the two components is similar to the Einstein radius (equation 5.2) corresponding to their combined mass. Mao & Paczynski (1991) estimate that for microlensing toward the bulge of the Milky Way, $\sim 10\%$ of the events will show strong binary characteristics. For microlensing toward the bulge by lenses of $1 \, M_\odot$ the Einstein radius is in the order of 5-10 AU in the lens and source plane. For self-lensing within M31 the Einstein radii are of the same order of magnitude. In this range binaries are uniformly distributed over log Period (Abt 1983, and references therein) and therefore also in log Separation. We can therefore expect that also in our survey $\sim 10\%$ of the self-lensing events will show strong binary behaviour. More subtle deviations from the standard microlensing behaviour will not be detected in low signal-to-noise events, and for high signal-to-noise events we use a more lenient $\chi^2$ criterium. This means that our theoretical predictions for M31 self-lensing should be scaled down by 10%.

### 5.8.3 Modeling results

Table 5 presents the theoretical predictions for the total number of events expected in the MEGA-INT four-year survey. The results are given for both self-lensing ($\mathcal{E}_{\text{self}}$) and halo lensing ($\mathcal{E}_{\text{halo}}$). The values quoted for $\mathcal{E}_{\text{halo}}$ assume $100\%$ of the halo is in the form of MACHOs. In other words, these values should be multiplied by the MACHO halo fraction in order to get the expected number of events for a MACHO component. We note that lensing by the Milky Way halo is not included in these results. This possible contribution is expected to be small, since the number of microlensing events from a 100% MW halo is a few times lower than for a 100% M31 halo (Baillon et al. 1993; Gyuk & Crotts 2000) for MACHO masses around $0.5 M_\odot$.

The near-far asymmetry of the events contains information about the contribution of halo lensing, and is therefore an important parameter. In figure 5.18 we show the cumulative
### Low extinction

Models with $\mathcal{M}_{\text{macho}}=0.5 \, M_\odot$ and $h_z=1.0 \, \text{kpc}$

<table>
<thead>
<tr>
<th>$(M/L)_d$</th>
<th>$(M/L)_b$</th>
<th>$\chi^2$</th>
<th>$\mathcal{E}_{\text{self}}$</th>
<th>$\mathcal{E}_{\text{halo}}$</th>
<th>$A_{\text{self}}$</th>
<th>$A_{\text{halo}}$</th>
<th>$A_{\text{ave}}$</th>
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<td>1.06</td>
<td>14.2</td>
<td>30.9</td>
<td>0.037</td>
<td>0.086</td>
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Models with $(M/L)_d=2.4$ and $(M/L)_b=3.6$

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<th>$\mathcal{E}_{\text{self}}$</th>
<th>$\mathcal{E}_{\text{halo}}$</th>
<th>$A_{\text{self}}$</th>
<th>$A_{\text{halo}}$</th>
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<td>0.037</td>
<td>0.085</td>
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### High extinction

Models with $\mathcal{M}_{\text{macho}}=0.5 \, M_\odot$ and $h_z=1.0 \, \text{kpc}$

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<thead>
<tr>
<th>$(M/L)_d$</th>
<th>$(M/L)_b$</th>
<th>$\chi^2$</th>
<th>$\mathcal{E}_{\text{self}}$</th>
<th>$\mathcal{E}_{\text{halo}}$</th>
<th>$A_{\text{self}}$</th>
<th>$A_{\text{halo}}$</th>
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Models with $(M/L)_d=2.4$ and $(M/L)_b=3.6$

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<th>$\chi^2$</th>
<th>$\mathcal{E}_{\text{self}}$</th>
<th>$\mathcal{E}_{\text{halo}}$</th>
<th>$A_{\text{self}}$</th>
<th>$A_{\text{halo}}$</th>
<th>$A_{\text{ave}}$</th>
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</thead>
<tbody>
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<td>1.06</td>
<td>11.2</td>
<td>30.5</td>
<td>0.052</td>
<td>0.095</td>
</tr>
<tr>
<td>G2</td>
<td>1.0</td>
<td>0.1</td>
<td>0.99</td>
<td>12.4</td>
<td>39.1</td>
<td>0.052</td>
<td>0.098</td>
</tr>
<tr>
<td>H2</td>
<td>1.0</td>
<td>1.0</td>
<td>0.99</td>
<td>12.4</td>
<td>23.8</td>
<td>0.052</td>
<td>0.093</td>
</tr>
</tbody>
</table>

**Table 5.5** – Results of the microlensing modeling using self-consistent M31 models. In the first columns some model parameters and the combined $\chi^2$ are listed. The remaining columns contain the predicted number of events due to self-lensing ($\mathcal{E}_{\text{self}}$), due to halo-lensing ($\mathcal{E}_{\text{halo}}$), the asymmetry of the self-lensing ($A_{\text{self}}$), of the halo-lensing ($A_{\text{halo}}$), and of the combination of both ($A_{\text{ave}}$). The number of self-lensing events $\mathcal{E}_{\text{self}}$ has been scaled down by 10% to account for the selection bias against events with binary lenses. The microlensing event rate due to the halo $\mathcal{E}_{\text{halo}}$ is for a 100% MACHO halo, i.e. all of the halo mass is assumed to be in the MACHOs. For calculating the combined self- and halo-lensing asymmetry parameter $A_{\text{ave}}$ a smaller fraction of the halo mass is assumed to be in MACHOs, namely the amount necessary to make up the difference, if any, between $\mathcal{E}_{\text{self}}$ and the observed number of 14 candidate events. The disk scale heights $h_z$ are $sech^2$ scale heights. The upper, low extinction part of the table contains models with internal extinction values as derived in section 5.7, while the lower, high extinction part contains models with increased extinction, as motivated by our analysis of the LPV amplitudes.
distribution of events for self and halo lensing as predicted by our model A1, as a function of the distance from the major axis, \( s \). We take \( s \) to be positive on the far side of the disk. Both self-lensing and halo-lensing contributions are scaled to give 14 total events. The dots show the distribution of the 14 candidate events in our sample. Both self- and halo-lensing do a good job of describing the event distribution in the inner 0.2°. The halo distribution does a somewhat better job of modeling the three events between \( s = 0.2° \) and \( s = 0.3° \). Neither halo nor self lensing models predict anywhere near two events for \( s > 0.35° \).

To easily compare the asymmetry with respect to the major axis, we define the asymmetry parameter \( \mathcal{A} \):

\[
\mathcal{A} = \sum \frac{\varepsilon_k(s) \cdot s_k}{\mathcal{E}}
\]  

(5.29)

where \( s \) is again the distance from the major axis in degrees, and \( \mathcal{E} \) is the predicted event rate. In table 5.5 the values for \( \mathcal{A}_{\text{self}} \) and \( \mathcal{A}_{\text{halo}} \) are given. We also provide an average \( \mathcal{A}_{\text{ave}} \) which assumes that MACHOs make up the shortfall between the expected number of events and the observed value of 14. In cases where the expected number of events is greater than 14, we set \( \mathcal{A}_{\text{ave}} = \mathcal{A}_{\text{self}} \). The asymmetry parameter for the 14 candidate events is \( \mathcal{A}_{\text{data}} = 0.125 \).

Timescales of microlensing events are determined by the transverse velocities of lens and source and by the Einstein radius, and are easily calculated from our theoretical models. Figure 5.19 shows the cumulative timescale distribution of our candidate microlensing events and our model A1. Both the curves for self- and halo-lensing are scaled to give 14 events in total. Within statistical errors, the data are consistent with the model predictions. This supports the microlensing nature of our candidate events and argues against a large contamination by variable stars or background supernovae.

Models A1 and A2 are the default models with the \( M/L \)'s and \( h_z \) motivated above and a MACHO mass of 0.5\( M_\odot \). Models B through H show the effect of varying key parameters. In the B and C models the bulge \( M/L \) is varied. This affects both the number of events as well as the asymmetry. A heavier bulge results in more bulge-bulge lensing events and since the bulge is heavily extincted on the near side, increasing the bulge-bulge lensing rate
boosts the asymmetry. The D and E models show the effects of varying the stellar mass in the whole galaxy. As expected, a higher $M/L$ increases the self-lensing rate and lowers the halo-lensing rate, since less mass can be put in the halo. The asymmetry of the self-lensing rate is hardly affected, but the asymmetry of the halo-lensing is. Models F1 and F2 have a vertical scale height two times smaller than the default models. This mostly affects the self-lensing, decreasing the expected number of events. The G and H models have MACHO masses of 0.1 and 1.0 M$_\odot$. These values of $M_{\text{macho}}$ are chosen in accordance with the most probable mass range for Milky Way MACHOs according to Alcock et al. (2000). Increasing $M_{\text{macho}}$ leads to a decrease of the number of halo lenses and thus to a decrease of $\varepsilon_{\text{halo}}$.

Looking at the table it is clear that in general the effect of extinction is a decrease in $\varepsilon_{\text{self}}$ and an increase in $A_{\text{self}}$. We also see that as the mass-to-light ratios are increased, $\varepsilon_{\text{self}}$ increases and $\varepsilon_{\text{halo}}$ decreases. There are some exceptions to these trends. For example in the heavy bulge case, models C1 and C2, $\varepsilon_{\text{self}}$ is higher for the high extinction model. The reason for this is that the bulge in this model is very heavy due to the combination of a high extinction correction to the minor axis SBP and the high bulge $M/L$. The resulting increase of bulge lenses overcompensates for extinguishing bulge and disk sources. Model C1 also gives a lower $\varepsilon_{\text{self}}$ than model A1, as the higher $(M/L)_b$ leads to a less massive disk. For each choice of mass-to-light ratios, the remaining parameters are adjusted to minimize $\chi^2$. This process can lead to rather complicated interdependencies between the model parameters.

### 5.9 Discussion

The expected number of events due to self-lensing is quite stable over all models that we probe in table 5.5. The relative insensitivity of $\varepsilon_{\text{self}}$ to changes in the mass-to-light ratios is a result of the way the models are constructed; changes in $(M/L)_b$ and $(M/L)_d$ are compensated by changes in the structural parameters of the disk, bulge, and halo to minimize $\chi^2$ for the fit to the rotation curve and surface brightness data. For example in models D1 and E1 the mass-to-light ratios differ by a factor of $\sim 2$ while $\varepsilon_{\text{self}}$ differs by only a factor of 1.4;
with the low $M/L$ values in model D1, the rotation curve data drive up the disk and bulge luminosity distributions at the expense of a poorer fit for the photometric data. A balance is struck, resulting in a change in $\mathcal{E}_{\text{self}}$ that is significantly smaller than what one might expect.

Within the statistical errors the total number of 14 observed events is consistent with the predicted number of self-lensing events, but also not inconsistent with a significant MACHO fraction in the halo of M31. To make this more quantitative we use the method of Feldman & Cousins (1998) and treat the detection of halo events as a Poisson process on a background of self-lensing events. Let $n$ be the number of observed events consisting of MACHO events with mean $f \mathcal{E}_{\text{halo}}$, where $f$ is the MACHO fraction, and a background due to self-lensing with known mean $\mathcal{E}_{\text{self}}$. The probability distribution function for $f$ is

$$P(n|f) = (f \mathcal{E}_{\text{halo}} + \mathcal{E}_{\text{self}})^n \exp \left[-(f \mathcal{E}_{\text{halo}} + \mathcal{E}_{\text{self}})\right] / n!.$$  \hspace{1cm} (5.30)

Confidence intervals for $f$ are calculated as follows. Calculate $P(n|f)$ for $N$ values of $f \in \{0, 1\}$ and sort from high to low. The maximum of $P$ defines the most probable value of $f$. Normalize the values of $P$ so that the sum of all sampled values of $P$ is 1. Sum the values of $P$ starting from the highest value until the sum exceeds the desired confidence level. The largest and smallest value of $f$ belonging to the the $P$-values that went into the sum define the confidence interval.

In table 5.6 we provide most probable values of $f$ and 95% confidence intervals for all of the models in table 5.5. We provide these values both for the case of the full sample of 14 observed candidate events ($n=14$), as well as for the case of 11 observed events ($n=11$), for reasons discussed below.
Table 5.7 – Observed number of events and the asymmetry of their spatial distribution, shown for the full sample of 14 events and for cases where the probable M32 event (11) and candidate events 13 and 14 are ignored. Also shown is the asymmetry for the long-period variable stars (LPVs).

<table>
<thead>
<tr>
<th>Events used</th>
<th>( \mathcal{E}_{\text{data}} )</th>
<th>( \mathcal{A}_{\text{data}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Full sample</td>
<td>14 0.125 ± 0.046</td>
<td></td>
</tr>
<tr>
<td>without 11</td>
<td>13 0.120 ± 0.049</td>
<td></td>
</tr>
<tr>
<td>without 13, 14</td>
<td>12 0.076 ± 0.034</td>
<td></td>
</tr>
<tr>
<td>without 11, 13, 14</td>
<td>11 0.066 ± 0.034</td>
<td></td>
</tr>
<tr>
<td>LPVs</td>
<td>20,864 0.071 ± 0.001</td>
<td></td>
</tr>
</tbody>
</table>

From table 5.5 we see that halo-lensing shows a significant asymmetry. This is due to the longer pathlength through the halo for lines-of-sight toward the far side of the disk than to the near side, the original argument for the asymmetry in the microlensing event rate being indicative for the presence of a microlensing halo. Self-lensing is also asymmetric, which is caused by the differential extinction. In all cases, \( \mathcal{A}_{\text{self}} < \mathcal{A}_{\text{halo}} < \mathcal{A}_{\text{data}} (= 0.125) \). The (weak) asymmetry in the self-lensing distribution is always a factor 2 or more lower than the halo-lensing asymmetry. Even for the high-extinction models, \( \mathcal{A}_{\text{self}} \) does not get anywhere near \( \mathcal{A}_{\text{data}} \). Although the halo-lensing asymmetry comes quite close to \( \mathcal{A}_{\text{data}} \), it is still lower in all models.

The asymmetry in the data is very large and cannot be reproduced even by pure halo-lensing. This high value of \( \mathcal{A}_{\text{data}} \) is largely caused by events MEGA-ML-11, -13, and -14 (see table 5.7). All of these events seem to be special cases for reasons that will be discussed now. Paulin-Henriksson et al. (2002) argue that it is likely that the event MEGA-ML-11 has a source star in M31, but a star in the satellite galaxy M32 as a lens. If so, it should not be included in the analysis of the event distribution, as it is not caused either by self-lensing within M31, nor by halo-lensing.

Events 13 and 14 are located very far from the major axis of M31 and difficult to explain by either self-lensing or halo-lensing. For model A1, the predicted number of self-lensing events with \( s > s(\text{event 18}) \) is 0.005 while the predicted number of MACHO events in the same range in \( s \) is 0.14f. Thus, the probability of having two events either from self or halo lensing is exceedingly small, unless the halo fraction is very large. However, since some contamination by variable stars of our sample can not be excluded, one or both of these events may be a variable star. We note, for example, that event 13 has the lowest S/N in our sample. The probability of having one event for MACHO lensing with \( f = 0.20 \) is \( \sim 3\% \), small, but not negligible. We also note that our models assume axisymmetry, and since M31 shows several non-axisymmetric features such as disk warping, our models may be inaccurate in some regions. According to the isophotal map by Hodge & Kennicutt (1982) event 13 lies on the \( B=24 \) (\( R=22.6 \)) contour while model A1 predicts \( R=23.5 \). Thus, the model may in fact underestimate the surface brightness of the disk by a factor of 2, and hence the disk-disk self-lensing rate by a factor of 4. (The reason for the discrepancy is not completely clear. The contours on the far side do appear to be “boxier” than those predicted by the model.)

It is interesting that events 13 and 14 are coincident with the location of the giant stellar stream discovered by Ibata et al. (2001). This stream runs across the southern INT field, approximately perpendicular to the major axis and over M32, which might be the progenitor
of the stream (Merrett et al. 2003). The average V-band surface brightness of the stream is $\Sigma_V \approx 30 \pm 0.5$ mag arcsec$^{-2}$ (Ibata et al. 2001) but this is measured far from the projected positions of events 13 and 14. The surface brightness of the stream might be significantly higher near the position of M32 (McConnachie et al. 2003). Perhaps the most conservative statement one can make about the stream is that it is not bright enough to distort the contours near events 13 and 14, that is, it cannot be brighter than the disk at these radii. The microlensing optical depth due to the stream $\tau_{\text{stream}}$ should relate to the self-lensing optical depth $\tau_{\text{self}}$ roughly as

$$\tau_{\text{stream}} \approx \frac{\Sigma_{\text{stream}}}{\Sigma_{\text{disk}}} \frac{D_{\text{stream}}}{h_{z,\text{disk}}} \tau_{\text{self}}$$

where $\Sigma_{\text{stream}}$ and $\Sigma_{\text{disk}}$ are the surface brightnesses of the stream and the disk, $D_{\text{stream}}$ is the distance between the stream and the disk along the line-of-sight, and $h_{z,\text{disk}}$ is the scale height of the disk. The first ratio must be smaller than 1, for the reasons mentioned above. $D_{\text{stream}}$ is not well constrained, but $D_{\text{stream}}/h_{z,\text{disk}}$ is probably of order 20, maybe up to 50. If close to M32 the surface brightness of the stream is around 10% that of the disk, this implies that $\tau_{\text{stream}}$ is of the same order as $\tau_{\text{self}}$. The stream-disk lensing rate might be further enhanced if the stars in the stream have a large proper motion relative to the disk. These arguments suggest that the number of stream-disk events in the vicinity of M32 might be as high as 0.1; perhaps high enough to explain one event.

In table 5.7 we show the values of $A_{\text{data}}$ for the full sample of 14 candidate events and for the cases where either event 11, events 13 and 14, or all of these are ignored. For comparison, we also list the asymmetry for the long-period-variables (LPVs) used in section 5.7 and discussed in detail in section 4.3.3 of this thesis. The errors in $A_{\text{data}}$ have been determined with the bootstrap method.

Figure 5.20 compares the asymmetry and number of events for the four cases in table 5.7 with the model predictions from table 5.5. The dots with error bars represent the data, while the solid circles with solid lines and the open circles with dotted lines represent the high-extinction and low-extinction models respectively. The circles assume pure self-lensing while the lines correspond to increasing MACHO halo fraction $f$ with the tick-mark indicating the position of $f = 0.2$. Once again, we see that the asymmetry parameter for the data is higher than that for any of the models. Removing events 13 and 14 improves the situation considerably. The high-extinction models are clearly in better agreement with the data than the low-extinction models.

Assuming that events 11, 13, and 14 are not caused by halo-lensing or self-lensing within M31, the data are consistent with the high-extinction models. Looking at table 5.6 shows that in this case for all but one model, the most probably MACHO fraction is $f = 0$. Without events 13 and 14, $A_{\text{data}}$ is also in very good agreement with the asymmetry of the LPVs, implying that both asymmetries are caused by extinction.

### 5.10 Conclusions

We present the analysis of four seasons of M31 data obtained at the INT. The goal of the analysis is to constrain the contribution of MACHOs to the halo of M31. A search for microlensing events using a fully automated search procedure results in 14 candidate microlensing events, of which three are reported here for the first time. The spatial and timescale distributions are consistent with microlensing.
Chapter 5: The compact object content of the M31 halo

Extensive Monte Carlo simulations of artificial microlensing events are used to determine our detection efficiency for microlensing events. Using the detection efficiency we calculate theoretical predictions for the microlensing event rate and distribution. These calculations are based on a suite of self-consistent disk-bulge-halo models for M31 and include a model for the extinction across the M31 disk. The sample of candidate microlensing events is compared to these theoretical predictions.

The results with regard to the fundamental question of whether there is a significant MACHO fraction in the M31 halo are inconclusive. Based on the total number of events, we find that the most probable MACHO halo fraction $f$ varies between 0 and 0.1 depending on the model. Our event rate analysis is consistent with a total absence of MACHOs as the confidence intervals for all of our models include $f = 0$. We cannot exclude some MACHO component, but a MACHO fraction of $f = 0.3$ or higher is excluded at 95% confidence for almost all models.

The spatial distribution of the candidate events is highly asymmetric and does seem to favour a MACHO component. However, for different reasons it is questionable whether the three candidate events that largely determine the asymmetry signal should be used in this analysis. Thus, we conclude that both from the observed number of events, and from their spatial distribution we find no evidence for the presence of MACHOs in the halo of M31.

5.A Candidate event lightcurves

On the following pages, for each of the 14 candidate microlensing events in our sample, the $r'$ and $i'$ lightcurves and thumbnails taken from the difference centered on the event positions are shown, together with a short discussion. Apart from the INT $r'$ and $i'$ data, KP4m R and I data points are also plotted in the lightcurves. The fits shown are however the fits done to only the INT data.
Figure 5.21 – (a) Event 1: lightcurves. The two upper panels show the full $r'$ and $i'$ lightcurves of the microlensing event. In the lower left corner are zooms on the peak region. In the lower right corner the $r'$ flux is plotted versus the $i'$ flux; if the colour is constant, the points should lie on a straight line. Also drawn is the best fit microlensing model. The solid circles are points from the INT data, the open circles are from the KP4m data. The start of the INT survey, August 1st 1999, is used as the zeropoint for the timescale.

<table>
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<td>$t_0$</td>
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</tr>
<tr>
<td>$t_{\text{FWHM}}$</td>
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</tr>
<tr>
<td>$\chi^2/N$</td>
<td>1.12</td>
</tr>
<tr>
<td>$\Delta\chi^2/N$</td>
<td>1.91</td>
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<tr>
<td>$r'$ N</td>
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</tr>
<tr>
<td>$i'$ N</td>
<td>137</td>
</tr>
<tr>
<td>$r'$ N($&gt;3\sigma$)</td>
<td>5</td>
</tr>
<tr>
<td>$i'$ N($&gt;3\sigma$)</td>
<td>5</td>
</tr>
<tr>
<td>$r'$ N(peak)</td>
<td>11</td>
</tr>
<tr>
<td>$i'$ N(peak)</td>
<td>5</td>
</tr>
</tbody>
</table>
Figure 5.21 – (b) Event 1: thumbnails. The two upper rows of thumbnails show are taken from $r'$ and $i'$ difference images during the peak of the candidate event. Selected thumbnails from the baseline are also shown in the two bottom rows. Each thumbnail is $30\times30$ pixels or $10\times10''$ in size.

**MEGA-ML-1**

Located close to the center of M31, this event has a rather noisy baseline. Apart from the background of very faint variables there are some variable sources clearly visible in the difference images. As can be seen in the thumbnails in figure 5.21(b) a bright variable is located just a few pixels from the position of the candidate event. Another, fainter variable is seen at a similar distance above and to the left. The other variable sources are further away and should have no influence on the photometry.
Figure 5.22 – (a) Event 2: lightcurves. See caption of 5.21(a).
MEGA-ML-2
This candidate event is located very close to MEGA-ML-1 and therefore has the same problems connected to being close the center of M31. In the thumbnails of days 94, 754, and 1208 we see a variable source a few pixels to the left of the event position. This variable is brighter in $r'$ than in $i'$, which causes the $r'$ baseline to be the most noisy.

Figure 5.22 – (b) Event 2: thumbnails. See caption of 5.21(b).
5.A. Candidate event lightcurves

Figure 5.23 – (a) Event 3: lightcurves. See caption of 5.21(a).
Figure 5.23 – (b) Event 3: thumbnails. See caption of 5.21(b).

MEGA-ML-3

This candidate event is also located close to the M31 center. In figure 5.6 we already demonstrated that a very faint variable source is positioned ~0.25"away from this candidate event. In the i' thumbnails another variable is visible just above and to the right of the event. This variable has a bright episode between days 440 and 480, causing the bump in the baseline in the i' lightcurve.
Figure 5.24 – (a) Event 7: lightcurves. See caption of 5.21(a).

MEGA-ML-7

t₀ = 71.8  \quad \chi^2/N = 1.98  \quad r' \text{ N}=146  \quad i' \text{ N}=138

\text{t}_{\text{max}} = 17.8  \quad \Delta\chi^2/N = 256.9  \quad r' \text{ N}(>3\sigma)=41  \quad i' \text{ N}(>3\sigma)=16

\quad r' \text{ N}(\text{peak})=42  \quad i' \text{ N}(\text{peak})=16
MEGA-ML-7

By far the brightest event in our sample, the thumbnails of MEGA-ML-7 show a very bright residual close to the peak center. Since the peak occurs during the first season, some of the exposures used for creating the reference image contained a significant amount of the magnified flux, so that the baseline lies at a negative difference flux. There are some variables nearby, but none of them are close or bright enough to significantly influence the photometry. The distance to the center of M31 is also quite large (~22'), reducing the background of faint variable sources. As pointed out by Paulin-Henriksson et al. (2003), there are some systematic deviations from the best fit microlensing model. An et al. (2004b) find that this anomaly can be explained by a binary lens.
Figure 5.25 – (a) Event 8: lightcurves. See caption of 5.21(a).

MEGA–ML–8

\[ t_0 = 63.3 \quad \chi^2/N = 0.82 \quad r' N = 154 \]
\[ t_{\text{max}} = 27.5 \quad \Delta \chi^2/N = 3.03 \quad r' N(>3\sigma) = 14 \]
\[ i' N(>3\sigma) = 5 \quad r' N(\text{peak}) = 49 \quad i' N(\text{peak}) = 22 \]
### MEGA-ML-8

This near side event is located \(~23'\) from the center of M31. A variable that is particularly bright in \(i'\) is situated about \(2.4''\) NW of the candidate event, but should not have much of an effect on the photometry. The baselines of the lightcurves indeed look stable and well-behaved.

![Figure 5.25 – (b) Event 8: thumbnails. See caption of 5.21(b).](image-url)

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![Baseline](image-url)

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<tbody>
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<td>![image]</td>
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<td>1096</td>
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</tr>
<tr>
<td>1248</td>
<td>![image]</td>
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</tr>
</tbody>
</table>
Figure 5.26 – (a) Event 9: lightcurves. See caption of 5.21(a).

MEGA-ML-9

\[ t_0 = 391.9 \quad \chi^2/N = 1.02 \quad r' N=156 \quad i' N=128 \]
\[ t_{\text{max}} = 2.3 \quad \Delta \chi^2/N = 2.49 \quad r' N(>3\sigma)=5 \quad i' N(>3\sigma)=5 \]
\[ r' N(\text{peak})=6 \quad i' N(\text{peak})=7 \]
Figure 5.26 – (b) Event 9: thumbnails. See caption of 5.21(b).

**MEGA-ML-9**

Peak coverage is poor for this candidate event, but the baselines are stable. The thumbnails show quite a lot of faint variables, two of which are located very close, approximately 1” to the left of the event position, accounting for the noise in the $i'$ baseline that is higher than in the $r'$ lightcurve.
Figure 5.27 – (a) Event 10: lightcurves. See caption of 5.21(a).

MEGA-ML-10

\[ t_0 = 75.9 \]
\[ \chi^2/N = 1.28 \]
\[ t_{\text{max}} = 44.7 \]
\[ \Delta \chi^2/N = 5.88 \]

\[ r' \ N = 149 \]
\[ r' \ N(>3\sigma) = 24 \]
\[ i' \ N = 121 \]
\[ i' \ N(>3\sigma) = 11 \]
\[ r' \ N(\text{peak}) = 47 \]
\[ i' \ N(\text{peak}) = 16 \]
MEGA-ML-10

This event is a beautiful example of a combined lightcurve with KP4m and INT data. Peak coverage in INT $i'$ is poor, but the KP4m I data points follow the fit (derived only from INT data) very well. A fairly bright variable is situated slightly above and to the right of the event position and there is a hint of a very faint variable about 1” to the left. Although the INT baseline in $i'$ is noisy, the $r'$ and both KP4m R and I lightcurves show an very stable and well-behaved baseline.
MEGA-ML-11

\[ t_0 = 488.4 \]
\[ \chi^2/N = 1.03 \]
\[ t_{\text{peak}} = 2.3 \]
\[ \Delta\chi^2/N = 13.27 \]
\[ r' N = 126 \]
\[ i' N = 101 \]
\[ r' N(>3\sigma) = 7 \]
\[ i' N(>3\sigma) = 5 \]
\[ r' N(\text{peak}) = 7 \]
\[ i' N(\text{peak}) = 8 \]

Figure 5.28 – (a) Event 11: lightcurves. See caption of 5.21(a).
MEGA-ML-11

A high signal-to-noise event with a good fit and stable baseline. There is some noise in the $i'$ baseline, caused by the variable source that is visible in the thumbnails of days 6 and 756 at $\sim 1.3''$ above the event position. During the fourth observing season a few bad columns were lying exactly on top of the event position, so that there is only 1 INT data point available. However, the KP4m data show that the baseline remains flat everywhere.
Figure 5.29 – (a) Event 13: lightcurves. See caption of 5.21(a).
This candidate event has the lowest signal-to-noise of our sample. It is situated far out in the far side of the disk at $\sim 31'$ from the center of the galaxy and the relatively low galaxy background makes it possible to detect these kind of faint events. Due to the y-axis scale the $i'$ baseline looks quite noisy, but it is in fact not significantly more so than for other candidate events. The thumbnails of days 398 and 520 show that the closest variable source is located $\sim 1.4''$ below and to the left of the event, which explains the scatter in the $i'$ baseline.
Figure 5.30 – (a) Event 14: lightcurves. See caption of 5.21(a).
MEGA-ML-14

At ~35.5’ from the M31 center, this candidate event is the most far out in the disk of all events in our sample. The $i'$ photometry of this candidate event is compromised by the variable source at ~1.3". From the $i'$ thumbnails one can also see that the event lies at the edge of a fringe, making the background in the lower half of the thumbnails brighter than in the upper half. This can also cause some extra scatter in the photometry. Overall, however, the microlensing fit is very good and both INT and KP4m lightcurves show a stable baseline.
MEGA-ML-15

\[ t_0 = 1145.5 \quad \chi^2/N = 1.23 \quad r' N(>3\sigma) = 9 \quad i' N(>3\sigma) = 8 \]

\[ t_{\text{max}} = 16.1 \quad \Delta\chi^2/N = 4.41 \quad r' N(\text{peak}) = 22 \quad i' N(\text{peak}) = 22 \]

Figure 5.31 – (a) Event 15: lightcurves. See caption of 5.21(a).
MEGA-ML-15

This event is again located close to the center of M31 and presumably has a strong background of faint variable sources. In the thumbnails also several variables are visible very close to the event position, both in $r'$ and in $i'$. The lightcurve baselines are rather noisy because of this, but show no coherent secondary bumps and the KP4m baselines are very stable.

Figure 5.31 – (b) Event 15: thumbnails. See caption of 5.21(b).
Figure 5.32 – (a) Event 16: lightcurves. See caption of 5.21(a).

MEGA–ML–16

t₀ = 13.4 \hspace{1cm} \chi^2/N = 0.93 \hspace{1cm} r' N(>3\sigma)=6 \hspace{1cm} i' N(>3\sigma)=0

t_{\text{peak}} = 1.4 \hspace{1cm} \Delta\chi^2/N = 2.81 \hspace{1cm} r' N(\text{peak})=8 \hspace{1cm} i' N(\text{peak})=0
Figure 5.32 – (b) Event 16: thumbnails. See caption of 5.21(b).

**MEGA-ML-16**

Not selected in our first analysis of the first two seasons of INT data (de Jong et al. 2004) due to baseline variability, the $i'$ lightcurve of this event is strongly influenced by a bright variable situated just 1.1'' to the north. Using a smaller extraction aperture for the photometry in the present analysis, the $i'$ baseline is still very noisy and the same is true for the KP4m I-band data. The INT $r'$ and KP4m R data are much better behaved and the $r'$ peak is fit very well by the microlensing fit.
Figure 5.33 – (a) Event 17: lightcurves. See caption of 5.21(a).
### Figure 5.33 – (b) Event 17: thumbnails. See caption of 5.21(b).

#### MEGA-ML-17

The $i'$ baseline is slightly noisy, but the $r'$ and both KP4m lightcurves are well-behaved. In the thumbnails no very close variables are visible.
Figure 5.34 – (a) Event 18: lightcurves. See caption of 5.21(a).
This candidate event shows quite large scatter in the baseline and also in the peak. Faint variables might be the culprits, although the event is not located very close to the galaxy center (~15.1'). The thumbnails show no variable sources very close to the event position, however they do show that this event is situated on the edge of a fringe running diagonally across the thumbnails. This fringe and the fact that it can change position slightly between frames is the most probable cause for the noisy $i'$ photometry.

**Figure 5.34 – (b) Event 18: thumbnails. See caption of 5.21(b).**