A Candidate M31/M32 Intergalactic Microlensing Event

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ABSTRACT

We report the discovery of a microlensing candidate projected $2'54''$ from the center of M32, on the side closest to M31. The blue color ($R - I = 0.00 \pm 0.14$) of the source argues strongly that it lies in the disk of M31, while the proximity of the line of sight to M32 implies that this galaxy is the most likely host of the lens. If this interpretation is correct, it would confirm previous arguments that M32 lies in front of M31. We estimate that of order one such event or less should be present in the POINT-AGAPE data base. If more events are discovered in this direction in a dedicated experiment, they could be used to measure the mass function of M32 up to an unknown scale factor. By combining microlensing observations of a binary-lens event with a measurement of the M31-M32 relative proper motion using the astrometric satellites *SIM* or *GAIA*, it will be possible to measure the physical separation of M31 and M32, the last of the six phase-space coordinates needed to assign M32 an orbit.

Subject headings: Galaxy: halo – M31: halo – lensing – dark matter

1. Introduction

Following the suggestions of Crotts (1992) and Baillon et al. (1993), the POINT-AGAPE collaboration[1] is carrying out a pixel lensing survey of M31 using the Wide Field Camera (WFC) on the Isaac Newton Telescope (INT). We monitor two fields of 0.3 deg^2 each, located North and South of the M31 center. The main goal of the survey is to map the global distribution of microlensing events in M31 and to determine any large-scale gradient. M31 is highly inclined, so there will be a strong gradient if a substantial fraction of the lenses lie in the dark halo of M31. The main difficulties are that the M31 sources are resolved only while they are lensed (and then only if the magnification is substantial), and seeing causes substantial variations in the point spread functions. The pixel lensing technique has been developed to cope with these problems (Ansari et al. 1997, 1999).

The large field of view happens to encompass M32, the dwarf elliptical, whose center lies $25'$ from the center of M31, corresponding to ~ 5 kpc in projected distance. Since M32 lies $\sim 53\overset{\circ}{.}5$ from the far-minor axis of M31, the M31 disk stars at this projected position are ~ 10 kpc from the center of M31. The M31 disk at this position is relatively faint and blue. Since M32 probably lies in front of M31 (Ford, Jacoby, & Jenner 1978), this opens up the possibility of detecting microlensing events of M31 stars by M32 stars (or other compact objects). Here, we report such a candidate M31/M32 intergalactic microlensing event. We argue from the geometry and color of the event that the intergalactic interpretation is the most plausible. The discovery of additional events of this type could be used determine the M32 mass function, as well as the relative distances and velocities of M31 and M32.

2. Observations and Data Analysis

Observations of the event, named PA-00-S4, were obtained in r' and i' bands (similar to Sloan r' and i') from 2000 August to 2001 January. The field was also observed in g' and r' bands from 1999 August to 2000 January, when the source was quiescent. Total exposure times were between 5 and 10 minutes per night. Data reduction is described in detail elsewhere (Ansari et al. 1997; Le Du 2000). After bias subtraction and flat-fielding, each image is geometrically and photometrically aligned relative to a reference image (1999

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[1] see `http://www.point-agape.org`

August 8), which was chosen because it has a long exposure time, typical seeing ($1.''5$) and little contamination from the Moon. The lightcurves are computed by summing the flux in 7-pixel ($2.''3$) square "superpixels" and removing the correlation with seeing variation. The transformation from instrumental (r', i') to Cousins (R, I) is based on ~ 50 standards (Haiman et al. 1994; catalogue II/208 of VizieR) that lie on the same CCD as PA-00-S4.

We use a simple set of criteria to select candidates from two seasons of INT WFC data. Detection of events is made in the r' band, which has better sampling and is free of fringing effects on the CCDs. We fit all lightcurves having detectable bumps to a Paczyński (1986) curve with seven parameters: the Einstein timescale $t_{\rm E}$, the time of maximum, t_0, the impact parameter (in units of the Einstein radius) u_0, and two flux parameters for each filter, one for the source F_s, and one for the background F_b. A bump is defined by at least 3 consecutive r' data points rising above the baseline by at least 3σ, with at least 2 points (in either band) on both the rising and falling parts of the variation (defined as the interval over which the lightcurve is at least $3\,\sigma$ above baseline). We calculate the probability P that the bump is due to random noise, and demand $-\ln P > 100$ in r' and $-\ln P > 20$ in the second filter (i' for 2000). To allow for non-standard microlensing events, we initially set a loose threshold of $\chi^2/\text{dof} < 5$. Then, to extract a sample of high signal-to-noise ratio events, we demand $R(\Delta F) < 21$, where $R(\Delta F)$ is the (Cousins) magnitude corresponding to $(A_{\rm max} - 1)F_s$ and $A_{\rm max}$ is the peak of the Paczyński fit. After eliminating the lightcurves with strong secondary bumps, there remain 362 candidates, of which 8 have FWHM shorter than 25 days. Four of these 8 short candidates are almost certainly microlensing events (Paulin-Henriksson et al. 2002). Among them is PA-00-S4, with a projected position close to the center of M32.

3. The M31/M32 Candidate

Figure 1 shows the lightcurves in r' and i' of PA-00-S4 together with the Paczyński fit. The source has J2000 position $\alpha = 00^{\rm h}42^{\rm m}30.0^{\rm s}$, $\delta = +40°53'47.''1$. That is, it lies projected on the far disk of M31, $22'31''$ from the center of M31, with a position angle $\sim 59.°2$ relative to the minor axis. It also lies $2'54''$ from the center of M32. There are some straightforwards tests to see if PA-00-S4 is compatible with microlensing. First there are no comparable "bumps" in the remainder of the lightcurve, as might be expected for many classes of variable stars. Second, it is achromatic: the r' and i' data are simultaneously fit to a Paczyński curve and show no significant systematic offset relative to one another. The FWHM of the peak is $t_{1/2} = 2.1\,$days, and at the maximum magnification the source is $R = 20.7 \pm 0.2$ (corresponding to $M_R = -3.9$) and $R - I = 0.00 \pm 0.14$. We know of no variables capable of producing a time-symmetric outburst of $2000\,L_\odot$ on such a short timescale. Note that the magnitude error is greater than the color error because the former is more affected by seeing. We assume a ratio of selective-to-total exinction $E(B-V)=0.062$ (Schlegel, Finkbeiner, & Davis 1998) and a distance of 770 kpc.

4. Lightcurve Analysis

4.1. Source Location

Microlensing events of unresolved sources are generically subject to a degeneracy in which the product of source flux F_s and the timescale $t_{\rm E}$ is much better determined than either parameter separately. PA-00-S4 suffers from this degeneracy at about the factor 2 level:

$$\log\frac{t_{\rm E}}{\rm day}=2.11\pm 0.34,\qquad R_s=26.65\pm 0.85. \tag{1}$$

Given the magnitude at peak, $R=20.7$, these correspond to a maximum magnification $A_{\rm max}=240^{+285}_{-130}$. At the distance and reddening of M31, the source flux corresponds to $M_R=2.05\pm 0.85$. This absolute magnitude and the dereddened color, $(R-I)_0=-0.05\pm 0.13$, are consistent with the source being either an A type main-sequence star or a blue horizontal branch (BHB) star. The former are expected to be common in the M31 disk, while about 8000 of the latter have been counted within a near-central $0.45\,{\rm arcmin}^2$ of M32. Given the short evolutionary phase of the BHB and the fact that the surface brightness of M31 is about twice that of M32 at this location, the source is strongly favored to be an M31 A star, even prior to the auxiliary information presented in § 4.2.

4.2. Lens Location

Current distance-indicator based estimates do not permit one to say whether M31 or M32 is closer (e.g., Mateo 1998). However, if M32 lay behind M31, it would suffer extinction due to dust in the M31 disk. The absence of such extinction as determined from a wide variety of observations led Ford, Jacoby, & Jenner (1978) to conclude that M32 must be in front. Moreover, the disk of M31 is disturbed (Argyle 1965; Einasto & Rümmel 1970; Gottesman & Davies 1970), leading Arp (1964) and Roberts (1966) to suggest an encounter with M32 as the cause. Byrd's (1976) model of this encounter, which has M32 passing right through the disk of M31, places M32 today 8.5 kpc in front of M31, i.e. $\sim 20\,{\rm kpc}$ in front of the M31 disk stars projected along the line of sight. In any case, M32 certainly lies in M31's potential well and orbits it rather closely: Faber (1973) argued from the profile of M32 that it had been tidally stripped by encounters with M31, and this has now been proved by the discovery of a Sagittarius-dwarf like tidal stream associated with M32 (Ibata et al. 2001).

For the moment, we assume that M32 lies 20 kpc in front of M31, in accordance with the estimate of Byrd (1976). Then there are six possible locations for the lens: the disk or halo of M31, the disk or halo of the Galaxy, M32 itself, or the tidal stream associated with it. The optical depth for any population, i, of lenses is $\tau_i = (4\pi G/c^2)\Sigma_i D_i$, where Σ_i is its surface mass density, and $D_i = D_{\mathrm{L},i} D_{\mathrm{LS},i}/D_{\mathrm{S}}$, a combination of the distances between the observer (O), lens (L), and source (S). For the populations under consideration, $D \simeq \min\{D_{\mathrm{L}}, D_{\mathrm{LS}}\}$.

The dereddened surface brightness of M32 at the position of the event is $R = 22.1\,\mathrm{mag\,arcsec}^{-2}$. Adopting a stellar (actually, compact-object) mass-to-light ratio of $M/L_R = 3$, this implies a surface density $\Sigma_{\mathrm{M32}} = 110\,M_\odot \mathrm{pc}^{-2}$. The optical depth is therefore $\tau \sim 1.4 \times 10^{-6}(D_{\mathrm{M31}} - D_{\mathrm{M32}})/20\,\mathrm{kpc}$. This is one to several orders of magnitude larger than the optical depths of the M32 tidal stream, the disks of M31 (Gould 1994) and the Milky Way (Gould, Bahcall & Flynn 1997), and to the optical depth due to compact objects in the Milky Way halo (Alcock et al. 2000; Lasserre et al. 2000). The total optical depth of the M31 halo at this location, if it were entirely composed of compact objects, would be $\tau_{\mathrm{M31}} \sim 4 \times 10^{-6}$. However, our current data already rule out a full MACHO halo for M31 (Paulin-Henriksson et al. 2002). If only 20% of the M31 halo were in compact objects, as Alcock et al. (2000) have argued is true for the Milky Way, then the M31 halo optical depth would be about half that due to stars in M32. We conclude that the most likely location of the lens is a star in M32 but that it could be a compact object in the halo of M31 as well.

4.3. Plausibility

What is the probability of finding a microlensing event for which the lens lies in M32 and the source in M31, and what is the most likely projected separation between such an event and the center of M32? At any given time, the expected number of events per unit surface area is

$$\frac{dn}{dA} = \frac{4\pi G}{c^2} N_{\mathrm{S}}(x,y)\Sigma_{\mathrm{L}}(x,y) D_{\mathrm{LS}} \tag{2}$$

where Σ_{L} is the surface mass density of lenses and N_{S} is the column density of sources. Integrating equation (2) over the entire M32 galaxy, and making the assumption (true to first order) that the source and lens densities are not correlated, yields

$$n_0 = \frac{4\pi G M_{\mathrm{M32}}}{c^2} D_{\mathrm{LS}} \langle N_{\mathrm{S}} \rangle = 40\,\frac{M_{\mathrm{M32}}}{10^9\,M_\odot}\,\frac{D_{\mathrm{LS}}}{20\,\mathrm{kpc}}\,\frac{\langle N_{\mathrm{S}}\rangle}{3\,\mathrm{pc}^{-2}}. \tag{3}$$

The quantities at the denominator of various ratios have been chosen to make those ratios close to unity. These adopted normalizations are derived as follows. For the total mass of M32, we assume an integrated luminosity of $M_B = -15.5$ (Krann-Korteweg & Tammann 1979), a color of $B - V = 0.9$ and a compact-object mass-to-light ratio of $M/L_V = 3.5$. We measure the M31 dereddened surface brightness at the radial position of M32 to be $R = 21.4\,\mathrm{mag\,arcsec^{-2}}$. If all of this light were typically coming from $M_R = 1$ stars, then there would be 3 pc^{-2} such stars. Only relatively high magnification events would be detectable with our current experimental setup. The number taking place at any given time with $A_{\rm max} > A_{\rm max,thresh}$ is $n \simeq n_0/A_{\rm max,thresh}$. To meet our selection criterion $R(\Delta F) < 21$ requires $A_{\rm max} > 70$. The measured color, $(R - I)_0 \sim -0.05 \pm 0.13$ and the color-luminosity relation of main-sequence stars favor a source luminosity at the bright end of the range given in equation (1), and so a timescale at the short end. We adopt $t_{\rm E} \sim 60\,\mathrm{days}$. Since $\pi t_{\rm E}/2 \sim 95\,\mathrm{days}$, we would detect $\sim (40/70) \times (150/95) \sim 1$ per observing season, assuming 100% efficiency. While we have not yet calibrated our efficiency, we expect that it is likely to be $\lesssim 10\%$ for this type of event ($A_{\rm max} > 75$, $t_{\rm E} \sim 60\,\mathrm{days}$) averaged over the relatively dense field of M32 (see below). So, we were somewhat lucky to detect such an event in the POINT-AGAPE database for 1999 and 2000, but not excessively so.

At what projected separation are we most likely *to detect* such an event? The surface brightness of M31 falls rapidly across the face of M32. We therefore first evaluate the probability for an event *to occur* in semicircular radial bins on each side of M32 by integrating the product of the M31 and M32 surface brightnesses over the bin (see eq. [2]). Figure 2 shows the result. As one moves from the center of M32 closer to M31, the probability is enhanced by the higher density of M31 sources, and by the larger size of the semicircle, but is degraded by the falling surface density of M32. On the side that is farther from M31, the surface brightness of both galaxies falls off rapidly, leading to a rapid decline in probability. Near the very center, our images are saturated, so there is no possibility of detection. The event PA-00-S4 lies on the shoulder of the probability curve, about a factor 10 below the peak. However, while events *occur* much more frequently near the center, they are not much more likely to be *detected*. Specifically, we find that a similar plot of variable stars detected with $R(\Delta F) < 21$ is roughly flat from the position of PA-00-S4 to the cutoff at $\sim 0\rlap{.}'5$. We conclude that the position of PA-00-S4 is a plausible place to detect such an event.

5. Possible Applications

There is a limited amount that can be concluded from one event, especially as we cannot be certain that the lens resides in M32 (see § 4.2). Nevertheless, it is worth considering the scientific applications of an ensemble of microlensing events in the neighborhood of M32, gathered not just in the experiments monitoring M31 but also perhaps in a future survey centered on M32 itself. First, if the events were clustered on the M31 side of M32 as predicted by Figure 2, then this would prove incontrovertibly that M32 lies in the foreground of the M31 disk.

Second, the distribution of Einstein timescales $t_{\rm E}$ can be used to measure the mass function of M32, modulo an initially unknown scale factor. The timescale is given by $t_{\rm E} = \theta_{\rm E}/\mu_{\rm rel}$, where $\theta_{\rm E}$ is the angular Einstein radius and $\mu_{\rm rel}$ is the source-lens relative proper motion. When, as in the present case, $D_{\rm LS} \ll D_{\rm S}$, this reduces to

$$t_{\rm E} \sim \frac{1}{v_{{\rm rel},\perp}}\sqrt{\frac{4GMD_{\rm LS}}{c^2}} = 73\,{\rm days}\biggl(\frac{v_{{\rm rel},\perp}}{300\ {\rm km\,s^{-1}}}\biggr)^{-1}\biggl(\frac{M_l}{M_\odot}\biggr)^{1/2}\biggl(\frac{D_{\rm LS}}{20\,{\rm kpc}}\biggr)^{1/2}, \qquad (4)$$

where $v_{{\rm rel},\perp} = |\mathbf{v}_{{\rm L},\perp} - \mathbf{v}_{{\rm S},\perp}|$ is the lens-source relative transverse velocity. The transverse velocity of the M31 disk at this location is known from its rotation curve and inclination and is $\sim 200\ {\rm km\,s^{-1}}$. The transverse velocity of M32 is unknown, but since M32 is in the potential of M31, its magnitude is likely to be $\sim 200\ {\rm km\,s^{-1}}$. Since these speeds are much larger than the internal dispersions of either population, $v_{{\rm rel},\perp}$ is probably $\sim 300\ {\rm km\,s^{-1}}$ and, very importantly, roughly the same for all events. Thus, if the timescales can be measured, the masses can also be measured, up to the unknown scale factor $v_{{\rm rel},\perp}^2/D_{\rm LS}$. We are unable to measure the timescale precisely in the case of PA-00-S4 because the source is not resolved in ground-based images, and so we do not know the source brightness which is degenerate with $t_{\rm E}$ (see eq. [1]). However, M31 microlensing sources can be resolved with the *Hubble Space Telescope* (e.g., Aurière et al. 2001). Indeed, virtually all potential sources in the field of M32 could easily be resolved with just 4 snapshots using the Advanced Camera System. Note that this mass-function measurement is very similar to Paczyński's (1994) proposal to measure the mass function of globular clusters that lie projected against the bulge, except that the distances and proper motions of the clusters are already reasonably well known, so there is no unknown scale factor.

Third, the ensemble of events would yield the product $M_{\rm M32}D_{\rm LS}$, according to equation (3). Combined with an independent estimate of $M_{\rm M32}$ (say, by assuming a compact-object mass-to-light ratio or by stellar dynamical modelling), this would give an estimate of $D_{\rm LS}$.

Fourth, if a caustic-crossing binary-lens event were observed, one could use it to measure $v_{{\rm rel},\perp}$. That is, if the source can be resolved in two bands, its surface brightness can be inferred from its color, and hence its angular size can be determined from its flux. The time that the source takes to cross the caustic (plus the crossing angle, which can be inferred from the solution of binary-lens geometry), then yields $\mu_{\rm rel} = v_{{\rm rel},\perp}/D_{\rm S}$. This technique has been successfully applied to five events (Albrow et al. 1999, 2000, 2001; Afonso et al. 2000; An et al. 2002). A determination of $v_{\rm rel,\perp}$ would remove some of the degeneracy in the mass-function measurement. This requires that the event be observed during the caustic crossing, which only lasts a time $2\Delta t = 2r_*/v_{\rm rel,\perp}\csc\phi = 4\,{\rm hr}(r_*/3r_\odot)/(v_{\rm rel,\perp}/300\ {\rm km\,s^{-1}})\csc\phi$, where ϕ is angle between the source-lens relative motion and the normal to the caustic. Hence, the crossing is unlikely to be observed unless special preparations are taken. Of course, this requires predicting the crossing in real time, as was done in all previous cases to which this technique has been applied.

Finally, we look ahead to combining microlensing and space-based interferometry to obtain all six phase-space coordinates of M32 relative to M31. At present, three of these coordinates are known (the two transverse position coordinates and the relative radial velocity), while the remaining three are unknown. The proper motion of M32 is $\mu_{\rm M32} = 60\mu{\rm as\,yr^{-1}}({\rm v_{L,\perp}}/200\ {\rm km\,s^{-1}})$. It will easily be measured by the *Space Interferometry Mission (SIM)* with its $\sim 4\,\mu$as precision and 5-yr baseline. It will also be measured by the scanning satellite *GAIA*, which will record the proper motions of $\sim 10^4$ stars in M32 with $\sim 100\,\mu$as precision, from which the proper motion of M32 itself is obtainable with $\sim 1\,\mu$as precision. Once the proper motion is determined, not only the magnitude of $\mathbf{v}_{\rm rel,\perp}$, but also its direction will be known. As we now describe, this can be combined with microlensing parallax information to determine $D_{\rm LS}$.

Normally, one does not think of parallax effects in relation to M31 microlensing, because the projected Einstein radius is so large,

$$\tilde r_{\rm E} = \sqrt{\frac{4GMD_{\rm S}D_{\rm L}}{D_{\rm LS}c^2}} \sim 460\,{\rm AU}\sqrt{\frac{M/M_\odot}{D_{\rm LS}/20\,{\rm kpc}}}, \qquad (5)$$

that it dwarfs any conceivable parallax baseline, whether space-based (Refsdal 1966) or ground-based (Gould 1992). However, parallax effects on a caustic crossing scale inversely with the projected source radius

$$\tilde r_* = \frac{D_{\rm L}}{D_{\rm LS}} r_* \sim 0.5\,{\rm AU}\biggl(\frac{D_{\rm LS}}{20\,{\rm kpc}}\biggr)^{-1}\frac{r_*}{3r_\odot} \qquad (6)$$

rather than as $\tilde r_{\rm E}^{-1}$ (Hardy & Walker 1995; Gould & Andronov 1999), and therefore could be precisely measured by a satellite in an Earth-like orbit even with relatively modest photometric capabilities. The time delay between the caustic crossings as seen from the Earth and satellite is

$$\delta t = \frac{D_{\rm sat}D_{\rm LS}\cos(\gamma-\phi)}{D_{\rm S}D_{\rm L}\mu_{\rm rel}\sin\phi}, \qquad (7)$$

where $D_{\rm sat}$ is the magnitude of the Earth-satellite separation vector projected onto the plane of the sky, γ is the angle between this projected vector and direction of source-lens relative motion, and where ϕ is again the angle between this motion and the normal to the caustic. As discussed above, $\mu_{\rm rel}$ can usually be measured from caustic crossings and ϕ can be determined from the overall solution to the binary event. Unfortunately, γ is not generally known, and hence the measurement of δt would not typically lead to a determination of $D_{\rm LS}$. However, since *SIM* or *GAIA* will measure the *vector* proper motions of M31 and M32 (and so determine the orientation of the M31-M32 relative proper motion as well), γ will in fact be known.

6. Conclusions

We have reported the discovery of a high S/N, short-duration microlensing candidate, PA-00-S4. It is a remarkable event because the source almost certainly lies in the M31 disk, yet the lens most probably resides in M32. This makes it the first convincing candidate for an M31/M32 intergalactic microlensing event. If this interpretation is correct, it demonstrates that M32 lies in front of M31. We estimate that $\lesssim 1$ such event satisfying the selection criterior $R(\Delta F) < 21$ should be detectable in the current POINT-AGAPE microlensing survey of M31.

The scientific applications of gathering an assemblage of events centered around M32 are substantial. If the events are clustered on the M31 side, this provides unambiguous evidence that M32 lies in front of M31. The events can be used to deduce the mass function of M32 up to an unknown scale factor. Microlensing observations of a binary-lens event, together with a measurement of the M31-M32 relative proper motion using astrometric satellites like *SIM* or *GAIA*, will enable the line-of-sight separation of M31 and M32 to be determined. This provides strong motivation for a microlensing survey targetted on M32 itself.

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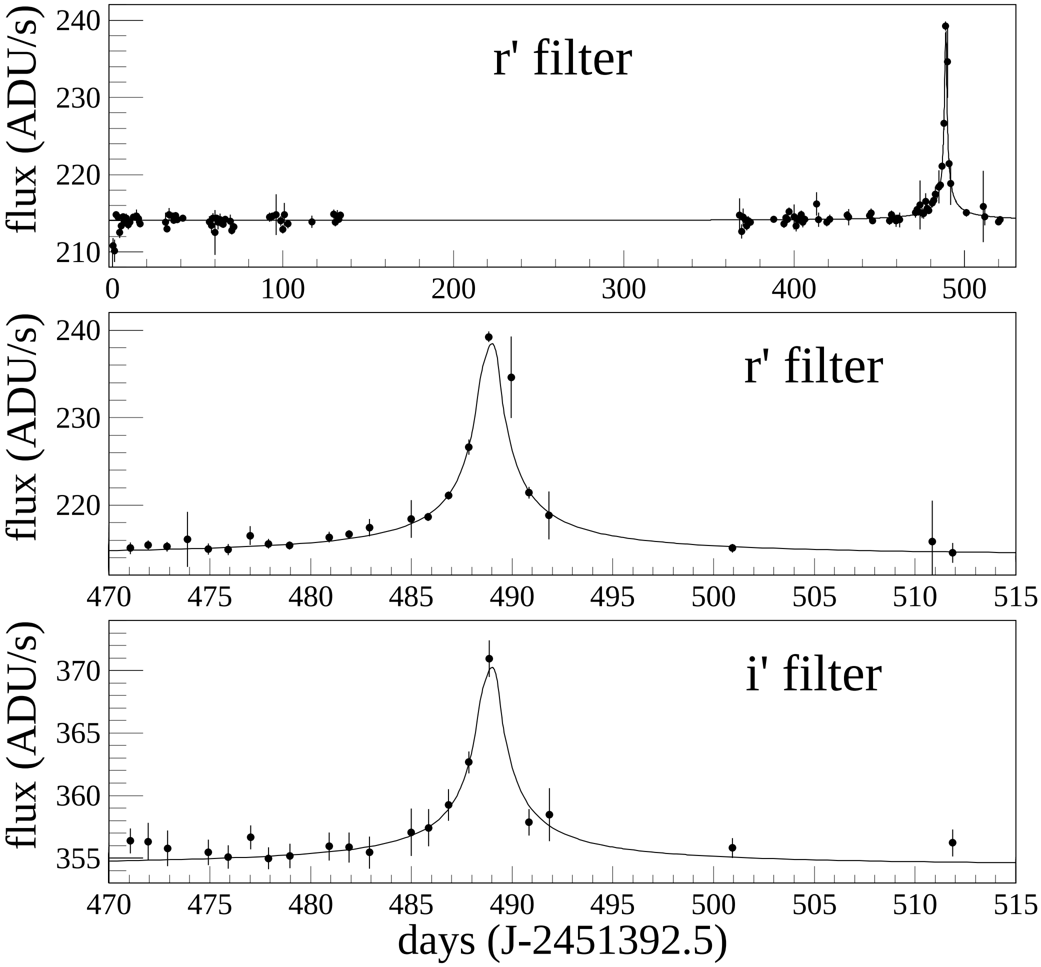

Fig. 1.— Lightcurves for the M31/M32 intergalactic candidate microlensing event PA-00-S4. Upper panel shows full two years of INT WFC data in r'. Lower two panels show zooms of the event in r' and i'. Both are well fit by a Paczyński curve with a single set of geometrical parameters.

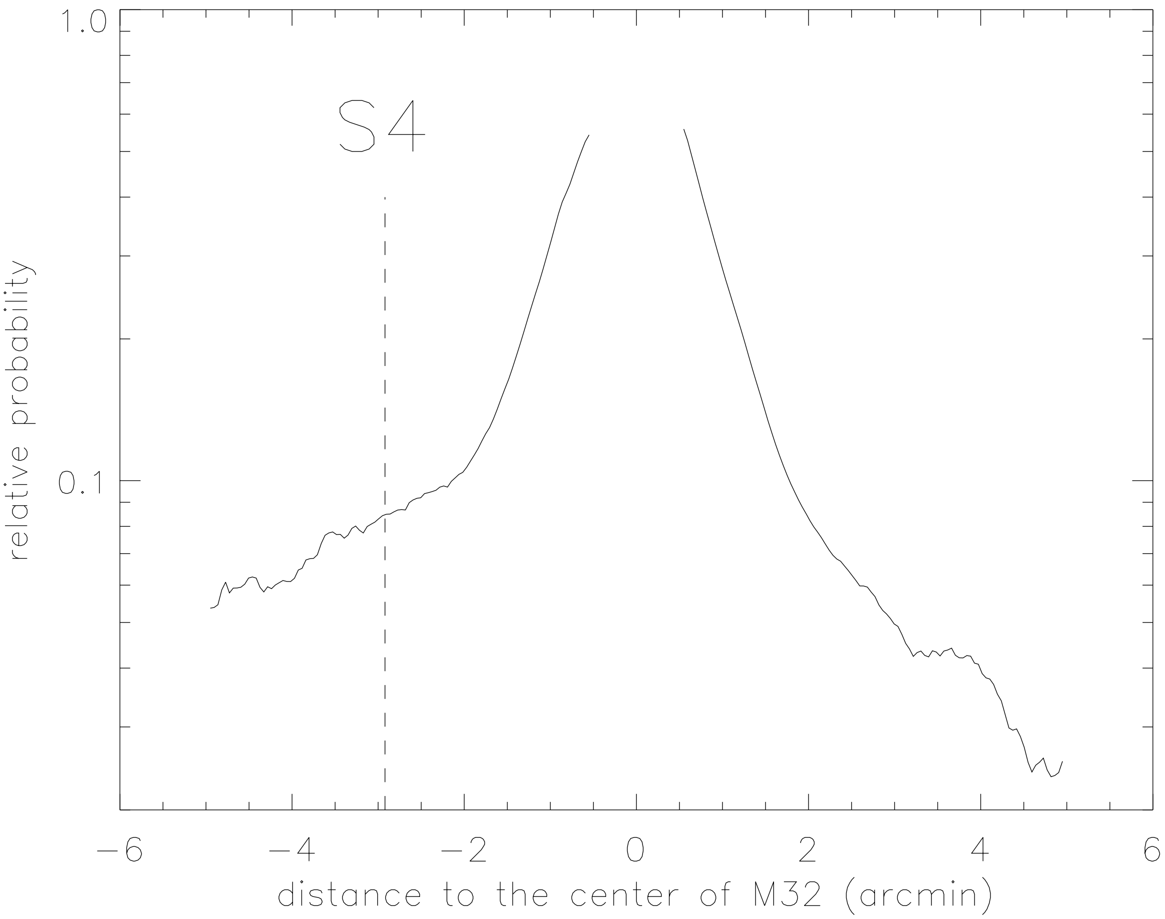

Fig. 2.— Relative probability for an event to occur in semi-circular radial bins around M32 on the sides closer to (negative) and farther from (positive) M31. The curve does not go to the center of M31, which is saturated. The event PA-00-S4 lies on the shoulder of this distribution, about a factor of 10 below the peak. However, the probability of *detecting* an event is roughly flat as a function of radius because the higher surface brightness interferes with detection.