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AGAPE Collaboration

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AGAPE
Andromeda Gravitational Amplification Pixel Experiment

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Abstract

The aim of the AGAPE (Andromeda Gravitational Amplification Pixel Experiment), experiment which has been first proposed in June 1992 is to examine the distribution of massive astrophysical compact halo objects ((MACHO's) which possibly are in the galactic haloes and which could account for the missing dark matter. Those objects have a mass which is a fraction of solar mass and could be detected by gravitational microlensing: the light of a star is amplified when a MACHO is crossing its line of sight from the earth. This technique has been proposed by Paczyński in 1986. The AGAPE collaboration applies this technique in an original way by using, as target stars, the stars of another galaxy without resolving them. The recent progresses in photometry with CCD allow now to see tiny variations of the surface brightness of a galaxy like M 31. Those tiny variations can be the result of a single microlensing event on the background stars contributing to the surface brightness. The AGAPE collaboration has now cumulated 82 nights of observation over 3 years at the 2m Bernard Lyot Telescope situated at Pic du Midi de Bigorre in the French Pyrénées and has found variations compatible with microlensing events.

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1 Introduction

The AGAPE (Andromeda Gravitational Amplification Pixel Experiment) collaboration followed an idea published in 1992 (Baillon et al. [1] and [2]). AGAPE searches for baryonic dark matter in the form of massive objects. Those objects, if they are numerous enough, could be responsible for the observed rotation velocity of the stars around the center of the galaxy where they belong. The experiment follows a modification of the microlensing technique proposed few years ago by Paczyński [3] and currently applied by several experimental teams: EROS(Aubourg et al. [5], Ansari et al. [4], Milsztajn [6]), MACHO(Alcock et al. [9][7, 8], Bennett [10], Sutherland [11]), OGLE(Udalski et al. [12, 13]) and DUO(Alard, Mao & Guibert [14], Alard [15]). microlensing occurs when a massive object (MACHO) is very closed to the line of sight of a star. The gravitational field of the massive object forces the light of the star to deviate and the massive object (MACHO) acts as an optical lense. It magnifies the amount of light reaching earth. The magnifying factor ranges from 1 to 10000 according to the distance x of the MACHO to the line of sight. (The deflection D of light by the MACHO is given by: $D = 2R_S/x$ where R_S is the Schwarzchild radius of the massive object; the amplification A is approximately given by the ratio $A = R_E/x$, where R_E is the Einstein radius:$R_E = \sqrt{2R_S d_b d_s/(d_b + d_s)}$, d_b is the distance of the MACHO to earth,d_s the distance of MACHO to the star, fig. 1).

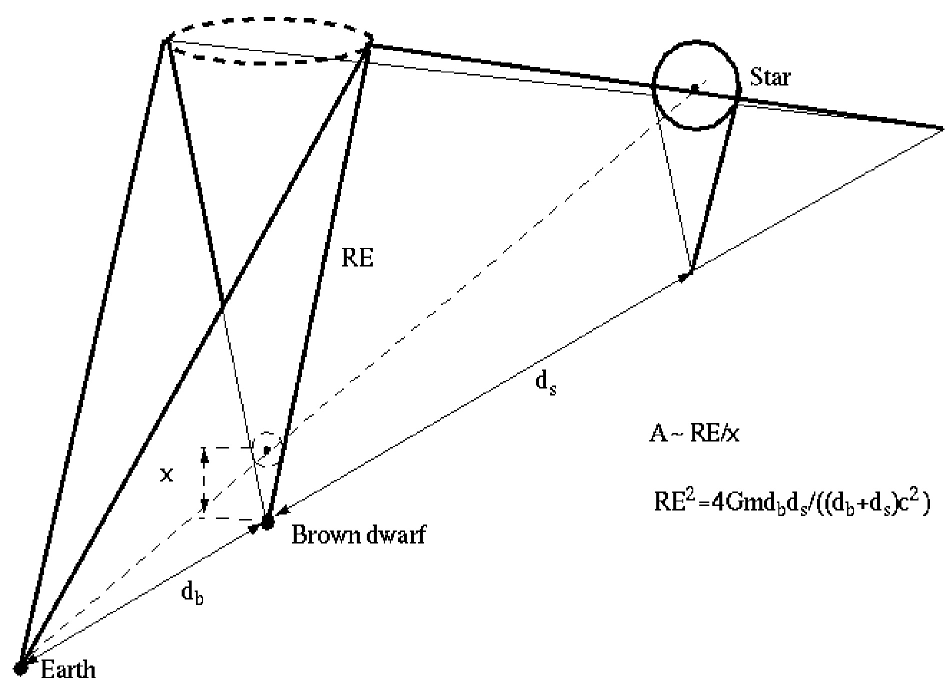


Figure 1: principle of the microlensing

Those first generation experiments search for microlensing events in a way we may call classical. They are monitoring about 10^7 stars and expect to see one of them making a measurable light excursion for several consecutive days. This technique was applied on stars of the two Magellanic Clouds and in the direction of the galactic bulge. They found a large number of events and microlensing is now well established. Fig. 2 shows some events found coming from the Magellanic Clouds.

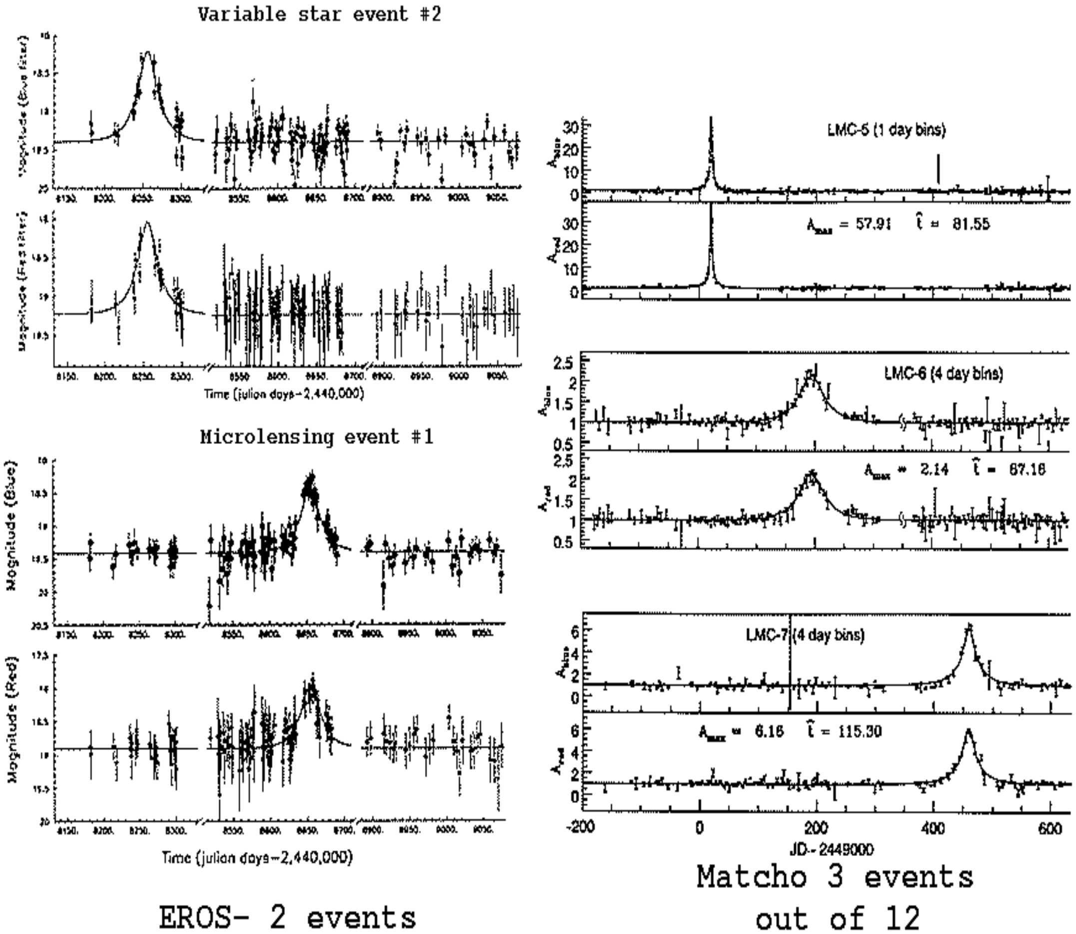


Figure 2: Events from the Magellanic Clouds

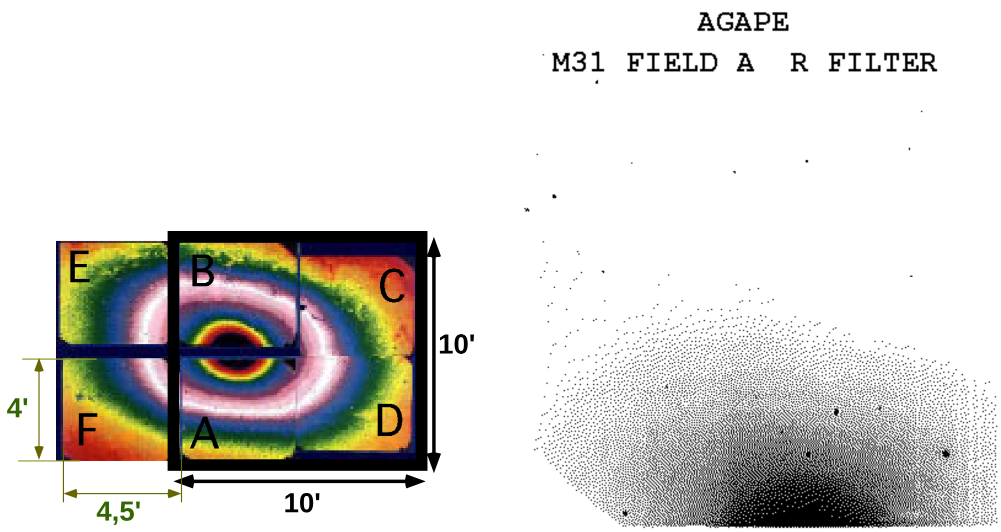
2 The AGAPE technique: "pixel method"

In order to go further and explore other regions of our galaxy, one has to give up the idea of monitoring individual stars. Our bulge and the Magellanic Clouds are the only directions where one can find 10^7 resolved stars at a known distance. For that reason, we proposed a new method called the "pixel method" which will make the rich fields of stars of nearby galaxies accessible. We implemented and applied this method to the Andromeda galaxy (M 31).[1, 2, 16]. A similar idea, relying on image subtraction, has been independently proposed by (Crotts [18]), and implemented by the Columbia-VATT collaboration (Tomaney & Crotts [19], Tomaney [20]).

In a dense field of stars, many stars contribute to any pixel of the CCD camera at the focal point of the telescope. However, if one *unresolved* star is sufficiently magnified, the increase of the light flux can be measured on the pixels located inside the star image. Therefore, instead of monitoring individual stars, we follow the luminous intensity of the pixels. Then *all* stars in the field, and not the only few resolved ones, are candidates for a micro-lensing; the event rate is potentially much larger. Of course, only the brightest stars will be amplified enough to become detectable above the fluctuations of the background, unless the amplification is very high and this occurs very seldom. In a galaxy like M 31, however, this is compensated for by the very high density of stars[17].

3 Observations of AGAPE

We took data at the 2m Bernard Lyot Telescope at Pic du Midi de Bigorre observatory in the French Pyrénées. Over the allocated periods [Oct.Nov. 1994,Aug.-Dec. 1995, Aug-Dec 1996] we obtained 82 half night of good weather with a typical seeing of 1.4" (best 0.9", worse 2.8"). The CCD camera had 800x900 useful pixels each of them covering 0.3"x0.3" in the sky. As the field of the telescope is small, we were led to cover the M 31 bulge with 6 fields (fields A, B, C, D, E and F of Fig. 3).



Approximate position of fields A to F in M 31

one picture

Figure 3:

It turned out that it was impossible to monitor all the fields in both colours each night. We decided to put a priority on the first four fields, with an emphasis on red exposures. Blue images, which require longer exposure times, were less regularly taken. Fields E and F were poorly sampled.The number of images taken in each field during the whole survey is summarized in Table 1.

Field	A	B	C	D	E	F
Red	84	73	67	59	46	38
Blue	33	33	24	19	10	8

Table 1: Number of pictures taken for each field in both colours, over the three periods of observation.

4 Alignment

The various pictures of the same area were taken at different times so they need to be realigned in position and in luminosity: the telescope does not come back exactly to the same position in the sky each time we took the same picture. The light absorption and background are not also the same so a realignment of the light flux has also to be

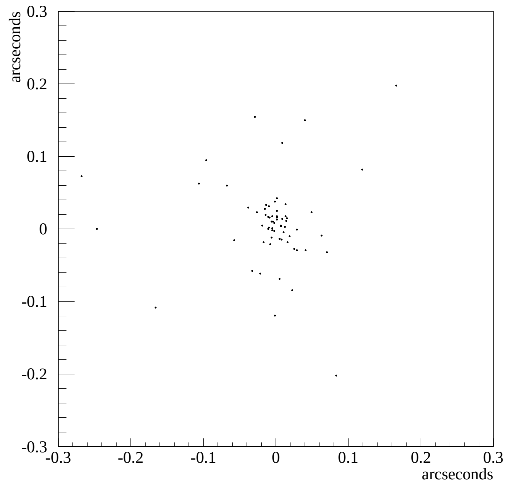


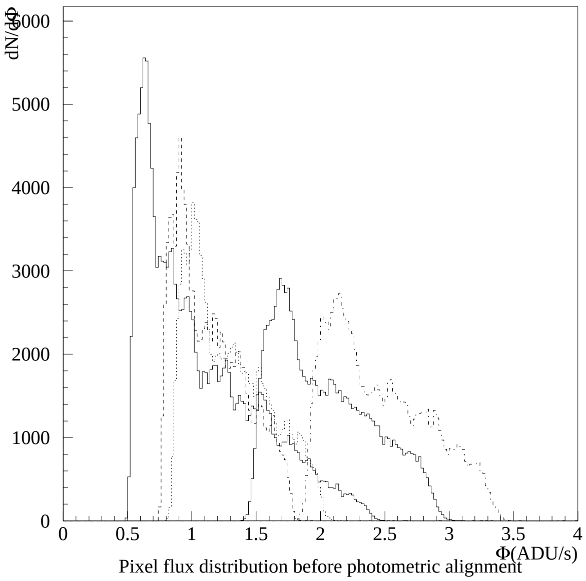
Figure 4: Dispersion of the difference of star positions between two images after geometric alignment

made. The geometrical alignment was done on stars which happen to be in front of M 31. The flux alignment was made by applying a linear correction so the two first moments of the light amplitude distribution on each similar picture are identical. The result of the geometrical alignment was much better than the telescope resolution (Fig. 4). On Fig. 5, the pixel flux distribution for various frames before and after the photometric alignment is displayed. From these graphs, it is clear that we are able to correct for any misalignment of the telescope and of the light flux measurements.

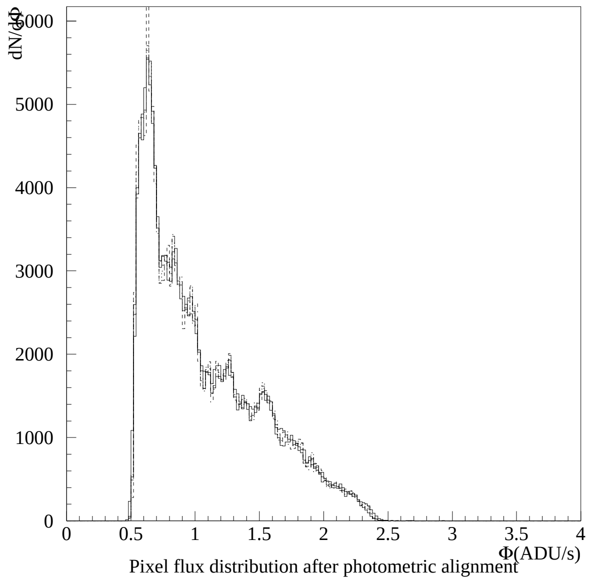
5 Seeing correction

A problem, which is not yet fully resolved, is to take into account the seeing variation. The M 31 background does not have a smooth behaviour: the amount of stars of M 31 in the telescope resolution is around a few thousands and is subject to poisson fluctuation. These fluctuations are also known as Tonry & Schneider fluctuations([21]). The telescope resolution is related to the *Psf* (Point Structure Function) which varies depending of the weather condition. The amplitude of those fluctuations as well as their shape are strongly dependant of the shape and size of the *Psf* . The changements of the *Psf* with time induce variations of the local fluxes registered by the pixels. Those variations are of the same order of magnitude as the effects we are looking at. It is important to have a good determination of those fluctuations when one suppresses the stable M 31 background from any pictures in order to extract their variable part. We approach this problem with two methods.

The first is an empirical method: On each picture we determine what is generally called a median (med) image. For each pixel l, we open a 41×41 window and find a value (ϕ^l_{med}) such as to have an equal amount of pixels with flux higher and lower than this value (ϕ^l_{med}). We assume that the difference between the value of the median and the measured value for each pixel is only due to the Tonry & Schneider fluctuations. This difference ($\phi - \phi_{med}$) should be zero for a poor seeing $S^{-1} \approx 0$, (S being the seeing). To first order in S^{-1}, the product of that difference by the seeing is independent of the seeing,



a



b

Figure 5: The matching of pixel histograms before (a) and after (b) photometric alignment

S. With the normalization, the median should the same for any picture. We conclude that for any pixel l and for any couple i,r of pictures we have the relation:

$$(\phi_i^l - \phi_{med}^l)S_i = (\phi_r^l - \phi_{med}^l)S_r$$

$$\phi_i^l - \phi_r^l = (\phi_r^l - \phi_{med}^l)(\frac{S_r}{S_i} - 1) = \alpha_{ir}(\phi_r^l - \phi_{med}^l) \tag{1}$$

On Fig. 6 top, we find indeed a linear relationship between $\phi_r^l - \phi_{med}^l$ and $\phi_i^l - \phi_r$. On the bottom picture, the various values of α_{ir} are compatible with an $\frac{S_r}{S_i} - 1$ relation drawn as a curve. The first attempt to reduce the effect of seeing is to estimate for each picture a picture close to a reference picture by inverting eq. (1)

$$\phi_i^{(est.)l} = \frac{\phi_i^l + \phi_{med}^l \alpha_{ir}}{1 + \alpha_{ir}} \tag{2}$$

.

The second method is more ambitious and requires a lot of computer time. One evaluates a distribution ψ^l depending of the pixel number l and a reduce Psf_i^k for each picture i,such as we have

$$\phi_i^l - a_i\phi_{med}^l \approx a_i \sum^k \psi^{l+k} \times Psf_i^k \ ; \ k,l \in \mathcal{Z} \odot \mathcal{Z}$$

Where k and l are treated as two dimensional integers that add as vectors and point to the cells of the CCD, a_i is the renormalisation factor for image i coming from the flux alignment. The domain of $l, k+l$ should be limited to the real size of the CCD and the domain of k is the one of Psf_i^k. The evaluation is done by a usual χ^2 minimization method with:

$$\chi^2 = \sum^{l,i} \frac{\left[a_i(\phi_{med}^l + \sum^k \psi^{l+k} \times Psf_i^k) - \phi_i^l\right]^2}{\phi_i^l} \tag{3}$$

One estimates all the ψ^l and Psf_i^k such as the χ^2 of (3) is minimum. The ψ^l represent the best estimation of the stable part of M31. This estimation can be put at the right seeing for picture i by convoluting it with the associated fitted Psf_i^k. It can be then subtracted from the picture i divided by a_i. The remaining part is the variable part. In order to be retained as coming from the variation of a stellar object, it should give rise, on several successives images, to a bump compatible with the corresponding Psf. The flux inside the Psf should be above zero by 5 standard deviations and should vary in time according to a Paczyński microlensing light curve [3].

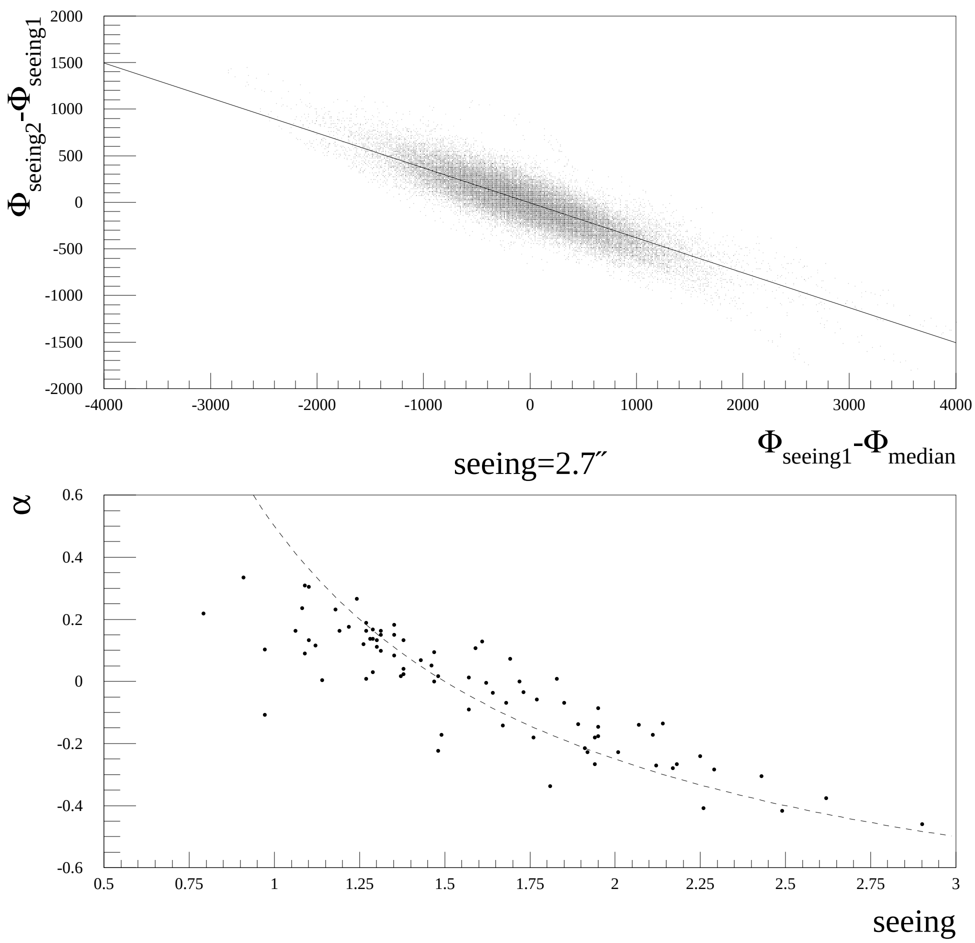


Figure 6: Seeing corrections (empirical)

6 The results

The results are still preliminary. We found $\approx$ 1000 local variations of light incompatible with a constant light emission by M 31. Most of these variations, however are certainly not microlensing events because they either repeat or are disymmetrical. Other variations are not retained as microlensing candidates, although some of them could be microlensing events, because we only see part of the light curve. The variation in Fig. 7 is probably a nova exploding in M 31 or a supernova exploding in one of the galaxy behind M 31.

In fig.8, we show some light curves compatible with microlensing events together with the fitted microlensing amplification light curve.

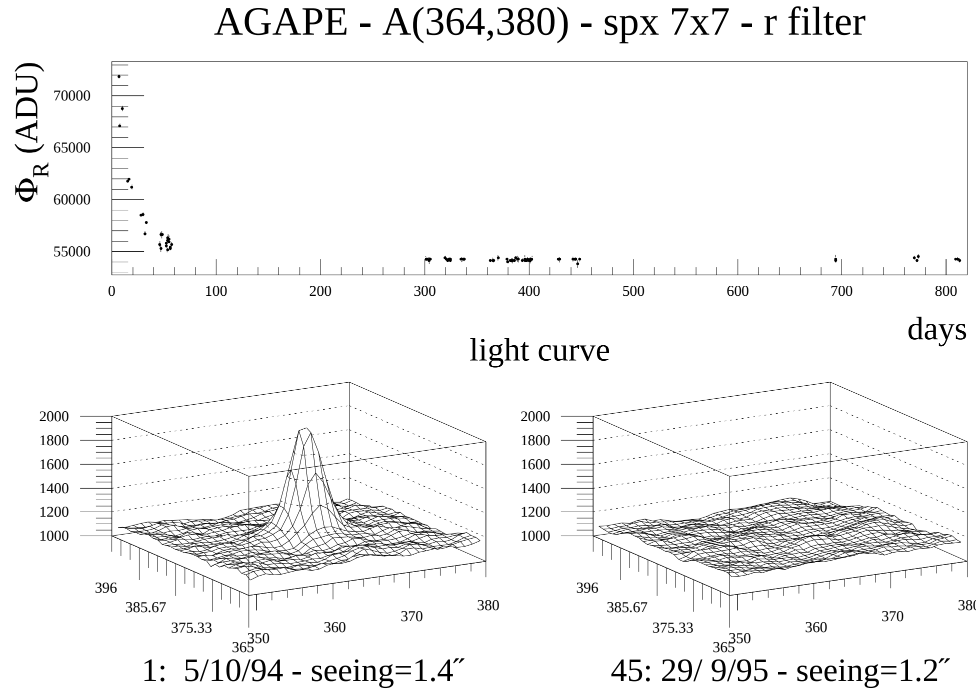


Figure 7: A Nova?

7 Perspectives

We plan to improve our seeing correction and our microlensing event selection. For the later point, we need more data over a long period of time, because it is crucial to be able to reject recurrent events.

In conclusion, AGAPE has proved that the pixel technique is a promising technique and we are looking forward to more data. Moreover, to exploit the full power of our method, we are exploring also the possibilities of starting an observation with a wide field camera on an instrument were we could get a very regular and short time sampling and a lever arm of several years. We would then be able to make a map of the halo of M 31, which would be of considerable interest for halo model builders.

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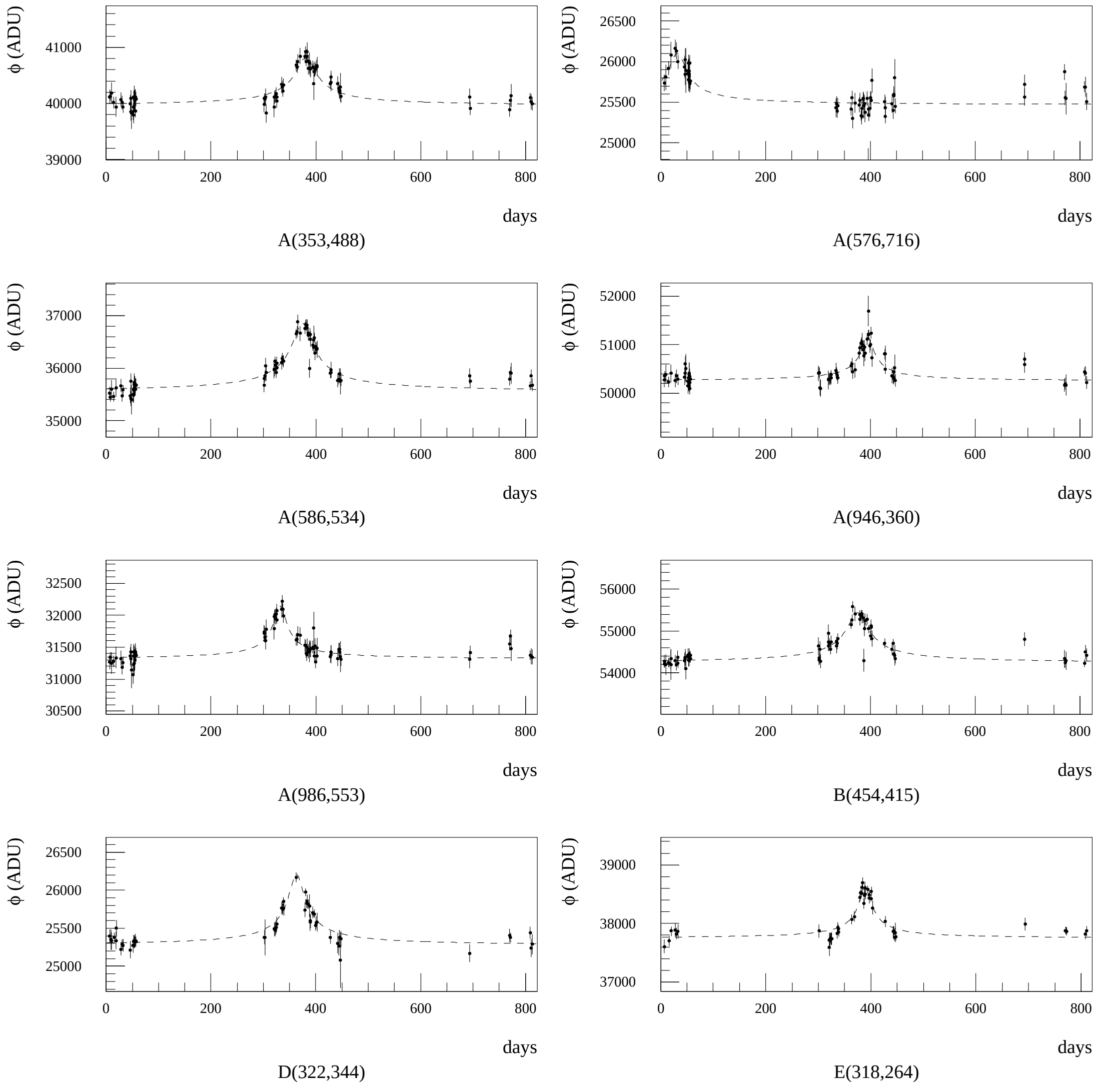

Figure 8: 8 light curves compatible with a microlensing event

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