AgapeZ1: a large amplification microlensing event or an odd variable star towards the inner bulge of M31 *

R. Ansari¹, M. Aurière², P. Baillon³, A. Bouquet⁴, G. Coupinot⁵, Ch. Coutures⁶, C. Ghesquière⁴, Y. Giraud-Héraud⁴, P. Gondolo⁶, J. Hecquet⁷, J. Kaplan⁴, A. Kim⁴, Y. Le Du⁴, A.L. Melchior⁸, M. Moniez¹, J.P. Picat⁷, and G. Soucail⁷

ABSTRACT. AgapeZ1 is the brightest and the shortest duration microlensing candidate event found in the Agape experiment. It occurred only 42″ from the center of M31 at $R = 18.0 (M_R - 6)$ with $B - R = 0.80$ mag color. A search on HST archives produced a single resolved star within the projected event position error box. Its magnitude is $R = 22$, and its color is compatible with that of the event at the 2σ level.

If the identification with the HST star is real, it implies for the event an amplification of about 4 magnitudes or 40 in brightness. This would lead to an Einstein crossing time radius of about 55 days. AgapeZ1 could be a bulge/bulge microlensing event involving a binary star.

The photometric properties of the object exclude classical M31 variable stars such as miras, novae, dwarf-novae, and bumpers. However, we cannot rule out the possibility that AgapeZ1 is in fact an odd variable star.

1. Introduction

The Agape experiment (Ansari et al., 1997) is devoted to the search of dark matter towards M31. It looks for gravitational microlensing effects on unresolved stars by the so-called pixel method (Baillon et al., 1992). In the active field of MACHO microlensing searches (Paczyński, 1996) only two groups explore the promising M31 direction (Crotts, 1992; Baillon et al., 1999), and though several events with light curves compatible with microlensing have been presented (Crotts and Tomaney, 1996; Le Du, 1998), all have lacked the strong supporting evidence needed for them to be classified as true microlensing events. The present work describes the properties of AgapeZ1 (hereafter called Z1), our brightest and shortest duration candidate which occurred only 42″ from the center of M31 in our central so-called “Z” field. The observational interest of our central field is manifold. It was observed at least once each of the 79 observing nights in R, and 30 nights in B. The central region of M31 has been observed by HST allowing for high-resolution archival searches for the quiescent sources of detected events. The central region of M31 is also of great astrophysical interest since it contains a huge number of stars. It is thus in this direction that the greatest number of microlensing events is expected to occur. However, because of the high star background level, only those with the highest amplification parameters will be resolved. A large number of variable stars, including exotic objects, may also be expected.

2. TBL observations and photometry

The Agape observations were made at the 2m Bernard Lyot telescope (TBL) of the Pic du Midi Observatory with the F/8 spectro-reducer ISARD. A thin Tektronik 1024x1024 CCD was used with a useful field of $4' \times 4.5'$ with 0.3″ pixels. The exposure times were generally 1 min in both the B and R passbands for the (Z) central field and 30(20) min in the B(R) passband for the 6 other fields.
investigated by the experiment (Ansari et al., 1997). We have 93 (30) R (B) exposures for field “Z” and 70 (33) R (B) exposures on the edge of a second field. The observing campaign ran from 1994 to 1996.

The Agape detection procedure is described in Ansari et al. (1997). It is based on the photometry in super-pixel (grouping of 7x7 pixels) with sides roughly two times the standard seeing. These super-pixels are photometrically normalised to a reference frame and corrected for seeing variations. The light curves for each super-pixel are analysed, yielding over 2000 variable objects. Of these, the 61 with only a single bump are then fitted with degenerate Paczyński curves (Wozniak and Paczyński, 1997). Selecting those with $\chi^2/dof<1.5$ leaves only 19 light-curves. After a cut on the color and the event duration (simulations described in section 4.1 show that 70% of expected microlensing events should have half intensity duration shorter than 40 days) we are left with only two candidates. Z1 is brighter, the shorter time-scale event and is located in the central bulge (Fig. 1). In our non central field containing Z1, it lies close to the edge where shadowing occurs which causes some systematic photometric uncertainty. However, because of their larger exposure times, the precision of the second field observations is greater than for the Z field ones. Fig. 2 shows the super-pixel light curve found by Agape for the object Z1. The days correspond to $J − 2449624.5$ where $J$ is the julian date.

To study the selected candidates, we developed a sophisticated photometry which will be described in a forthcoming paper (Baillon et al., 1998). Our procedure belongs to the so-called image subtraction technics, already used by Tomaney and Crotts (1996) and Alard and Lupton (1998). It is based on a global fit of one PSF (10x10 parameters) for each image and a unique reference background field (200x200 parameters). As it takes seeing effects more efficiently into account than does the super-pixel photometry described in Ansari et al. (1997) we found its results more accurate, with however still 15% systematic uncertainty.

![Fig. 1](image1.png)

Fig. 1. a. Recenetr sum of 26x1 mn exposure B frames onto Z1 position. a. B 30 mn exposure image of a 30”x30” field centred on Z1 at maximum brightness.

![Fig. 2](image2.png)

Fig. 2. $R$ super-pixel photometry light curve of AgapeZ1 for all measurements in the central Z (empty dots) and 2$^{nd}$ field (filled dots).

![Fig. 3](image3.png)

Fig. 3. Improved photometry R light curve of Z1 for the event period (1995 season). The points are fitted with a degenerate Paczyński curve of parameters $R_{\text{max}} = 18.0$ and $t_{1/2}=4.8\pm0.2$,days.

Fig. 3 shows an enlargement of the improved photometry light curve of Z1 at the time of the event, averaging the star fluxes measured on the 2 fields when available. Apart from a (significant) bump at day $≈428$, a good fit of a Paczyński curve ($t_{1/2}=4.8$ days) is obtained (data for 1994 and 1996 seasons are also used for the fit). At maximum, on 16 december 1995, the R magnitude is found to be $R=18.0$ and the color $B−R=0.80$. We have four color measurements during the event. The color at maximum has accurate precision (0.05 mag. stat.) since the corresponding B image is a 30 min exposure. Because of the faintness of the star or short exposures, the three other measurements cannot be used to tightly constrain achromaticity.

3. HST observations of the Z1 field

The Z1 event positional error box lies on a series of HST WFPC2 archive taken on 9 September 1994 as part of a single observing program$^1$ (The PI was R. Bohlin from STScI). There were no change in pointing between each exposure. We studied one 2300 s image taken with the

---

$^1$ Based on observations made with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute. STScI is operated by the Association of Universities for Research in Astronomy, Inc. under the NASA contract NAS 5-26555.
F656N filter and two co-added images with an effective exposure of 1200 s taken with the F547M filter.

We have computed the spatial transformation between the Agape and HST fields with a least square reduction based on 10 common stars. The standard deviation for the projection accuracy of the standard stars is 0.06″ and is mainly due to the uncertainties on the position of the stars in the Agape fields. We have projected the position of Z1 onto the HST images with a 3σ uncertainty of 0.18″ and found a faint star (R ∼ 22 mag) 0.14″ away from the projected position. It is the only resolved star on the HST image nearer than 0.4″ from the Z1 projection. We call this star HST1. Fig. 4 shows a negative print of the HST field for the Z1 projected region.

**Fig. 4.** Negative print of F547M HST image of a 2.6"x2.6" field centred on HST1 and showing the 3σ error box for Z1 projected position.

We use the DAOPHOT package (Stetson, 1987) to perform PSF fitting on the star. Since the field is crowded and there are no bright stars near our candidate, we used the theoretical PSF of TINYTIM. The standard magnitudes from the PSF photometry are $m_{F656N} = 21.6 \pm 0.2$ and $m_{F547M} = 21.9 \pm 0.1$ which are consistent within error from the results obtained from aperture photometry.

4. Interpretation

4.1. *Agape*Z1 as a microlensing event

On Fig. 5 we show two plots obtained from Monte-Carlo simulations which include the known characteristics of the two galaxies (M31 and Milky Way), and, for each, an isothermal halo filled with 0.5 $M_\odot$ machos. With respect to simulations described in (Ansari et al., 1997), 0.6 $M_\odot$ M31 bulge lenses are added. Simulations give the distributions of the V magnitude of lensed stars and of the effective duration ($t_{1/2}$ defined as the FWHM of the amplification peak in the lightcurve) of the event expected for a microlensing effect detected with the same criteria as in our selection process.

If Z1 is interpreted as being due to a microlensing amplification of HST1, the event characteristics ($V \sim 22$ and $t_{1/2} = 4.8$ days) are fully compatible with those expected considering these simulations. In this case the magnification is of 4 magnitudes or 40 in brightness and the Einstein radius crossing time is about 55 days. This is typical for a microlensing event between bulge-bulge stars with a mass of 0.6 $M_\odot$ which is expected whatever is the nature of the halo or for a microlensing event between a halo macho of 0.5 $M_\odot$ and a M31 star.

Now, in this hypothesis, HST1 and Z1 must have the same color and the same spectral type. After correcting for the galactic extinction of $E_{B-V} = 0.08$ (van den Bergh, 1991) with the extinction model of Cardelli, Clayton & Mathis (1989), we find that Z1 has the $B - R$ color of an F5 star (Allen, 1973). The color and magnitude of HST1 are consistent also with an F5II star at the 2σ level. However F5II stars are rare and only some tens are found in huge spectroscopic catalogs (Houk and Fesen, 1978). They correspond to a very short stage in stellar evolution of massive stars. For example, using a “Geneve” model (Schaller et al., 1992) we find that it would correspond to a subgiant of 4 $M_\odot$ (between the main sequence and the helium flash).

The color and magnitude of HST1 can also be attributed to a highly reddened supergiant. However, such a large extinction is unlikely in M31 considering Han (1990) measurement of a uniform $A_V = 0.24$ disk extinction. We thus prefer the identification of HST1 as an F5II star.

The fit with a Paczyński model ($t_{1/2} = 4.8$ days) is good for all points except for a statistically significant bump two days before the rapid rise to maximum. The shape of this lightcurve could be explained by the presence of a binary source (Griest and Hu, 1992) or a binary lens (Stefano and Perna, 1997). The binary source hypothesis...
could explain the odd color of Z1/HST1 and the possible difference of color between the two objects.

Finally, Z1 could be a microlensing amplification of a fainter star, blended or not with HST1. In this case the source would be at least 1 magnitude fainter than HST1, and the amplification greater than 100.

4.2. AgapeZ1 as a variable star:

M31 variable stars could mimic microlensing events. For example, Crotts and Tomaney (1996) point out the possible pollution of their sample of candidates by very long period Miras, some of which they have already discarded. In the case of Z1, its blue color definitively excludes this hypothesis.

Della Valle and Livio (1996) explored the possibility that dwarf novae could contaminate microlensing survey samples. For observed dwarf novae, colour ranges between $B-V = -0.1$ and $B-V = +0.6$ and main outburst amplitude ranges between 2 and 5 magnitudes (Warner, 1995). Thus the colors of HST1 and Z1 as well as the amplitude of the event are consistent with a dwarf nova outburst. However, the quiescent absolute magnitude of dwarf novae is around 7 with a rather large range (Warner, 1995). If HST1 and Z1 correspond to a dwarf nova, the object would be in the foreground, well outside M31 and in the Galactic halo within 10 kpc from the sun. The existence of such an object exactly projected towards the inner bulge of M31 is rather unlikely. There exists a broad relation between outburst amplitude and outburst interval for dwarf novae (Warner, 1995): for a 4 magnitude amplitude, one can expect outbursts to occur with intervals smaller than 100 days. In this case, the repetition of the Z1 event could be observable with follow-up observations.

Bumpers are variable stars which were detected by the MACHO experiment (Alcock et al., 1996). These objects have small amplitudes, unlike Z1 event.

Although the overall appearance of Z1 is similar to that of a nova, its faint magnitude would imply a long rate of decline while we observe a rapid one (0.25 magnitude per day observed, for 0.02-0.04 magnitude per day expected from the relation established by Capaccioli et al. (1989) for M31 novae). Reconciliation with the Capaccioli et al. trend would require Z1 to have a reddening of around 2 magnitudes in the visible which would imply a $E_{B-V}$ reddening of about 1 magnitude. The Agape experiment observed ten M31 novae, two being in the “Z field”, and nine having $B-R$ colors. All the novae for which the respective data are available follow the Capaccioli et al. (1989) trend and/or they have a $B-R$ color near maximum in the range 0.4-0.6 (apart from one which is strongly reddened near maximum). The color of $B-R = 0.80$ at maximum for Z1 is thus not what would be expected for an M31 nova reddened by 2 magnitudes in the visible.

5. Conclusion

Our work shows that the AgapeZ1 event could be due to the gravitational amplification of a F5III color binary object corresponding to HST1 with an Einstein radius crossing time of 55 days. On the other hand the photometric properties of Z1 are incompatible with those of a classical M31 variable star. The foreground dwarf novae hypothesis appears unlikely. However, the inner bulge of M31 may be the site for rather odd objects. We have thus compared the position of Z1 with those of already known exotic objects including the 1885 supernovae (de Vaucouleurs and Corwin, 1985), the X-ray sources (Primini et al., 1993; Trinchieri et al., 1991), and novae observed up to the inner bulge by (Ciardullo et al., 1987). Z1 is located about 6" from the position of the transient X-ray source E47 but the chance of association is weak. However, Z1 could be an unknown kind of cataclysmic variable. New Z field Agape observations are on the way to monitor for a recurrence of Z1 and to search for similar objects in the bulge of M31.

References

Alard, C. and Lupton, R.: 1998, ApJ 503, 325
Alcock, C. et al.: 1996, ApJ 461, 84
Allen, C.: 1973, Astrophysical Quantities, The Athlone Press
Ansari, R. et al.: 1997, A&A 324, 843
Baillon, P. et al.: 1992, in P. Fleury and G. Vacanti (eds.), Proceedings of the first Palaiseau Workshop, p. 151, Editions Frontières, Gif sur Yvette
Baillon, P. et al.: 1993, A&A 277, 1
Baillon, P. et al.: 1998, in 36th INFN Eloisatron Workshop on New Detectors Erice (Italy) November 1997
Capaccioli, M. et al.: 1989, AJ 97, 1622
Cardelli, J. et al.: 1989, ApJ 345, 235
Ciardullo, R. et al.: 1987, ApJ 318, 520
Crotts, A. and Tomaney, A.: 1996, ApJ 473, L87
Crotts, A. P.: 1992, ApJ 399, L43
de Vaucouleurs, G. and Corwin, H.: 1985, ApJ 295, 287
Della Valle, M. and Livio, M.: 1996, ApJ 457, L77
Di Stefano, R. and Perna, R.: 1997, ApJ 488, 55
Griest, K. and Hu, W.: 1992, ApJ 397, 362
Han, G. G., 1996, ApJ 472, 108
Houk, N. and Fesen, R.: 1978, in A. D. Philip and D. Hayes (eds.), The HR Diagram, p. 91
Le Du, Y.: 1998, in J. Kaplan and M. Moniez (eds.), 4th International Workshop on Gravitational Microlensing Surveys, IAP and Collège de France, Paris
Paczynski, B.: 1996, Annual Review of Astronomy & Astrophysics 34
Primini, F. et al.: 1993, ApJ 410, 615
Schaller, G. et al.: 1992, A&A 250, 629
Stetson, P.: 1987, PASP 99, 191
Tomaney, A. and Crotts, A.: 1996, AJ 112, 2872
Trinchieri, G. et al.: 1991, ApJ 382, 82
van den Bergh, S.: 1991, PASP 103, 1053
Warner, B.: 1995, *Cataclysmic variable stars*, Cambridge University Press
Wozniak, P. and Paczyński, B.: 1997, *ApJ* 487, 55