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LETTER

Letter to the Editor

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

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Abstract. AgapeZ1 is the brightest and the shortest duration microlensing candidate event found to date in the Agape experiment. It occurred only $42''$ from the centre of M31 at $RA = 0^h42^m41.47^s$ and $Dec = 41°16'39.1''$ (J2000). Our photometry shows that the half intensity duration of the event is 5.3 days and at maximum brightness its magnitude is $R = 17.9$ ($M_R \sim -6$) with $B - R = 0.80$ mag colour. A search on HST archives produced a single resolved star within the projected event position error box. Its magnitude is $R = 22$, and its colour is compatible with that of the event at the 2σ level.

If this event is identified with the HST star, the implied amplification is about 4 magnitudes or 40 in brightness. This would lead to an Einstein crossing time radius of about 60 days. AgapeZ1 could be a bulge/bulge microlensing event involving a binary star.

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

Key words: Galaxy: halo – cosmology: observations – cosmology: dark matter – cosmology: gravitational lensing

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 pixel method (Baillon et al., 1992; Baillon et al., 1993). In the active field of MACHO microlensing searches (Paczyński, 1996) only two groups explore the promising M31 direction (Crotts, 1992; Baillon et al., 1992), and though several events with light curves compatible with microlensing have been presented (Crotts & Tomaney, 1996; Le Du for the AGAPE collaboration, 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 centre of M31 in our central "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 the 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 2 m Bernard Lyot telescope (TBL) of the Pic du Midi Observatory with the F/8 spectro-reducer ISARD. A thinned 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 central (Z) field and 30(20) min in the B(R) passband for the 6 other fields investigated by the experiment (Ansari et al.,

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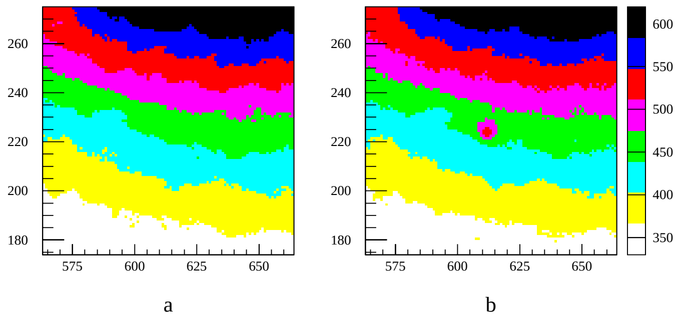

Fig. 1. a A sum of 26 one minute exposure B-band $30'' \times 30''$ sub-images centered on the Z1 position. **b** The equivalent field of the 30 mn B-band image containing Z1 at maximum brightness.

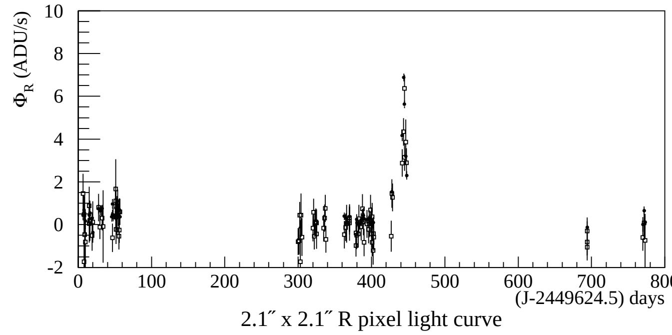

Fig. 2. R super-pixel photometry light curve of AgapeZ1 for all measurements in the central Z (empty dots) and 2^{nd} (filled dots) fields.

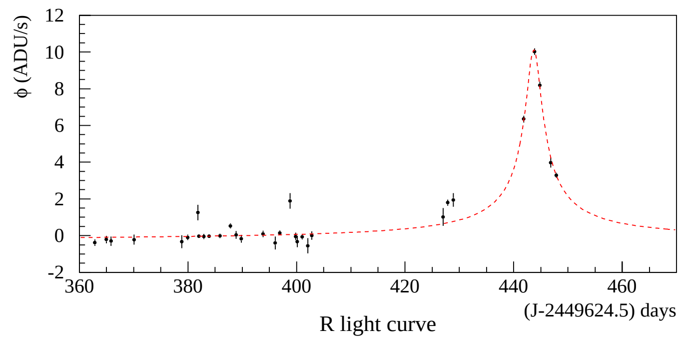

Fig. 3. Improved photometry R light curve of Z1 for the event period (1995 season). The points are fit with a degenerate Paczyński curve, yielding $R_{max} = 17.9$ mag and $t_{1/2}$=5.3±0.2 days.

1997). We have 93 (30) R (B) exposures for field "Z" and 70 (33) R (B) exposures of a second field on whose edge Z1 fortuitously lies. 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 groupings of 7x7 pixels, 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 to yield over 2000 variable objects. Of these, the 61 with only a single bump are then fit with degenerate Paczyński curves (Wozniak & Paczyński, 1997). Selecting those with $\chi^2/dof < 1.5$ leaves only 19 light-curves. After a cut on the colour and the event duration (simulations described in Sect. 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 the brighter, shorter time-scale event and is located in the central bulge (Fig. 1). In the 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 those of the Z field. 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 analysis which will be described in a forthcoming paper (Ansari et al., 1999; Baillon for the AGAPE collaboration, 1998). Our procedure uses image subtraction techniques, such as those used by Tomaney and Crotts (1996) and Alard and Lupton (1998) and is based on a global fit of one PSF (10x10 parameters) for each image and a unique reference background field (200x200 parameters). As it accounts for seeing effects more efficiently than the super-pixel photometry described in Ansari et al. (1997) we found its results more accurate, with however 15 % systematic uncertainty.

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. We performed a Paczyński parametrised fit on this light curve using all the data between day 360 and day 470 except the 3 points at day ~ 428. The global χ^2 is 57 with 24 degrees of freedom.

At maximum, on 16 December 1995, the R magnitude is found to be R=17.9 and the colour $B - R = 0.80$. We have four colour measurements during the event. The colour 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 event or their 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 archival images taken on 9 September 1994 as part of the program "The Nucleus of Normal and Starburst Galaxies" (proposal ID #5121, R. Bohlin PI)[1]. There was no change in pointing between each exposure. We studied one 2300 s image taken with the 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 of the star positions on the Agape images. We have

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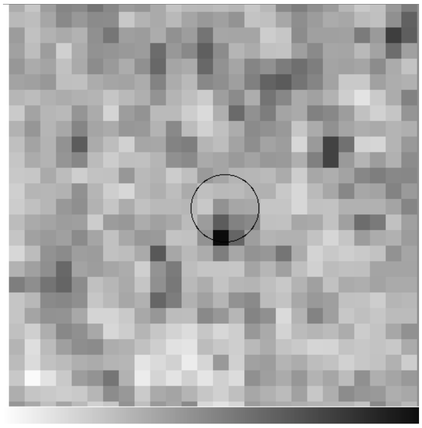

Fig. 4. Negative print of a 2.6″x2.6″ field taken from the F547M HST image, centred on Z1 and showing the 3 σ error circle for the Z1 projected position.

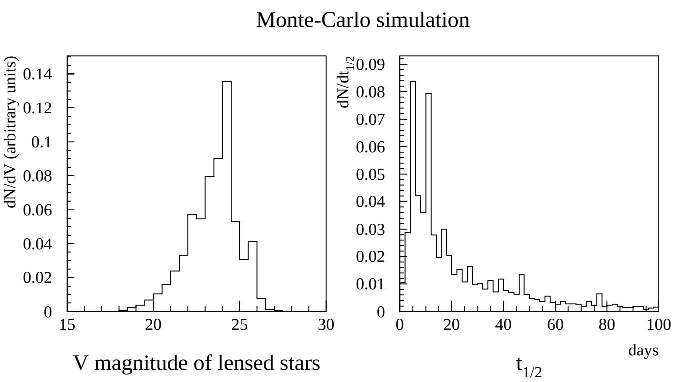

Fig. 5. Distributions of the unlensed V magnitudes of stars that are lensed and of the effective durations of the events expected for microlensing effects on M31 stars by both stars of the M31 bulge and MACHO's belonging to the halo of M31 or of our own Galaxy.

projected the position of Z1 onto the HST images and found a faint star ($R \sim 22$ mag) $0.14''$ away from the projected position. It is the only resolved star on the HST image closer 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.

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 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 with the results obtained from aperture photometry.

4. Interpretation

4.1. AgapeZ1 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 as described in (Ansari et al., 1997) plus additional 0.6 $M_\odot$ M31 bulge lenses. Simulations give the distributions of the (unlensed) V magnitude of stars that are lensed 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 $t_{1/2} = 5.3$ days) are fully compatible with those expected considering these simulations. In this case the magnification is 4 magnitudes or a factor of 40 in brightness and the Einstein radius crossing time is about 60 days. This is typical for a microlensing event between bulge-bulge stars with a mass of 0.6 $M_\odot$, independent of the nature of the halo, or for a microlensing event between a halo MACHO of 0.5 $M_\odot$ and a M31 star.

With this hypothesis, HST1 and Z1 must have the same colour 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 $B - R$ colour of an F5 star (Allen, 1973). The colour 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 & 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 colour and magnitude of HST1 can also be attributed to a highly reddened supergiant. However, such a large extinction is unlikely in M31 considering the Han (1996) measurement of a uniform $A_V = 0.24$ disk extinction. We thus prefer the identification of HST1 as an F5II star.

As we already explained, the fit with a Paczyński model ($t_{1/2}$=5.3 days) is satisfactory 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 & Hu, 1992) or a binary lens (Di Stefano & Perna, 1997). The binary source hypothesis could explain the odd colour of Z1/HST1 and the possible difference of colour 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 one 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 relatively blue colour definitively excludes this hypothesis.

Della Valle & Livio (1996) explored the possibility that dwarf novae could contaminate microlensing survey samples. For observed dwarf novae, colour ranges between $-0.1 \leq B - V \leq +0.6$ and main outburst amplitudes range between 2 and 5 magnitudes (Warner, 1995). Thus the colours 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 of 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.

The overall appearance of Z1 is similar to that of a nova, but its rapid rate of decline (defined as the average rate, in mag/day, at which a nova drops to two magnitudes below maximum) would imply a bright rather than the observed faint peak brightness. The decline rate–peak magnitude relation plotted by (Capaccioli et al., 1989) using a sample of 105 M31 novae leaves a scatter smaller than 0.6 mag. The behaviour of the six novae with observed maximum discovered by Agape is consistent with this plot. For Z1 however, the decline rate of 0.25 magnitudes per day (derived from an observed decline of 1 magnitude) predicts an observed peak more than two magnitudes brighter than Z1. The Capaccioli et al. (1989) sample does contain two outlying objects with similar decline rates and peak magnitudes to Z1; Arp 4 is possibly a heavily obscured nova and Rosino 48 is a suspected recurrent nova. It is nonetheless unlikely that Z1 is a very reddened nova as only one of 105 novae in their sample might be significantly extincted and it is generally supposed that there is minimal absorption towards the centre of M31 (Hatano et al., 1997). The observed Z1 colour also does not support heavy extinction; $A_V = 2$ mag leads to a colour excess of $E(B-R) = 1.1$ mag (Schmidt-Kaler, 1982). With this amount of extinction, the bluest nova observed by Agape would then have $B - R = 1.5$, significantly redder than the observed 0.8 colour observed for Z1 at maximum, even considering the large photometric uncertainties. (Note that the significance of novae colours have to be considered with caution since emission lines play an important role in the brightness of these objects). If Z1 were a recurrent bursting star, it would enter in the category of an odd cataclysmic variable, a possibility that we cannot discount. We have thus compared the position of Z1 with those of already known exotic objects including the 1885 supernovae (de Vaucouleurs and Corwin, 1985), X-ray sources (Primini et al., 1993; Trinchieri & Fabbiano, 1991), and novae observed up to the inner bulge by (Ciardullo et al., 1987). The closest exotic found is the transient X-ray source E47 but with a separation of $6''$ the chance of their being associated is weak.

5. Conclusion

Our work shows that the AgapeZ1 event could be due to the gravitational amplification of a F5II-colour binary object corresponding to HST1 with an Einstein radius crossing time of 60 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, including odd cataclysmic variables. 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.

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