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## The star pile in Abell 545<sup>★</sup> (Research Note)

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### ABSTRACT

**Context.** Struble (1988, ApJ, 330, L25) found what appeared to be a cD halo without cD galaxy in the center of the galaxy cluster Abell 545. This remarkable feature has been passed almost unnoticed for nearly twenty years.

**Aims.** Our goal is to review Struble's claim by providing a first (preliminary) photometric and spectroscopic analysis of this "star pile".

**Methods.** Based on archival VLT-images and long-slit spectra obtained with Gemini-GMOS, we describe the photometric structure and measure the redshift of the star pile and of the central galaxy.

**Results.** The star pile is indeed associated with Abell 545. Its velocity is higher by about 1300 km s<sup>-1</sup> than that of the central object. The spectra indicate an old, presumably metal-rich population. Its brightness profile is much shallower than that of typical cD-galaxies.

**Conclusions.** The formation history and the dynamical status of the star pile remain elusive, until high S/N spectra and a dynamical analysis of the galaxy cluster itself become available. We suggest that the star pile might provide an interesting test of the Cold Dark Matter paradigm.

**Key words.** galaxies: clusters: individual: A 545 – galaxies: elliptical and lenticular, cD – galaxies: intergalactic medium

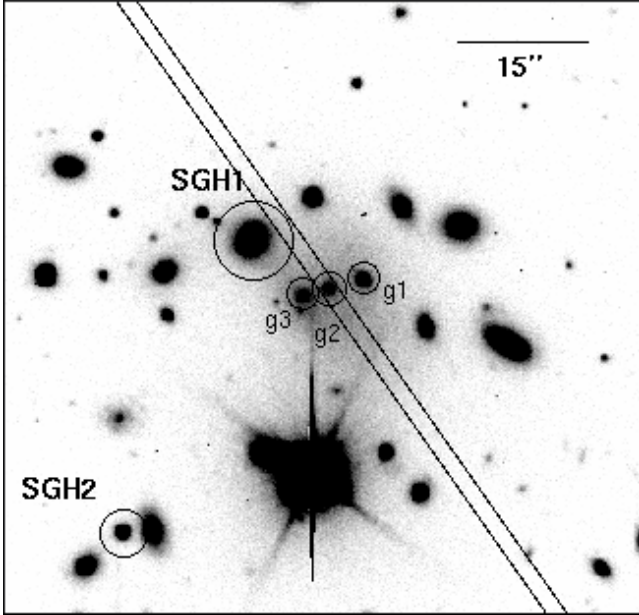
### 1. Introduction

In recent years, intracluster stellar populations have been recognized as an important component of the baryonic mass in clusters of galaxies. Their study can constrain their total baryonic budget, their interaction history, and the enrichment of the intracluster medium (e.g. Gonzalez et al. 2007; Gerhard et al. 2007; Zaritsky et al. 2004). Stellar populations visible as intracluster light (ICL) can contribute up to 50% of the total stellar mass (Lin & Mohr 2004), although much lower numbers have also been reported (Zibetti et al. 2005; Krick & Bernstein 2007). In the present article, we focus on a phenomenon which is possibly related to the overall ICL, but much more concentrated to the center of a galaxy cluster: the "star pile" in Abell 545.

Abell 545 ( $z = 0.152$ , Schneider et al. 1983) is one of the most massive galaxy clusters known. With a richness class of 4, it is the second richest in the Abell catalogue (Abell et al. 1989). While many clusters of this richness host a massive central cD galaxy, Struble (1988) found on Palomar Sky Survey (POSS) plates in the center of Abell 545 a diffuse and very faint extended structure, which he labelled "star pile", apparently a cD-halo without a cD galaxy. Struble suggested that this was "the first probable discovery of intracluster matter" in a rich cluster from visual inspection of the POSS, although he admitted the possibility that this object may not belong to Abell 545, but instead being a Galactic nebula projected onto Abell 545. However, he also cites a private communication by J. Schombert, which suggested a reddish colour from a Palomar 5 m uncalibrated CCD-image. Since Struble's paper there has been no published follow-up work on this intriguing object. The paper has been mentioned a few times, but until today, even the confirmation as an extragalactic object is pending.

Assuming an association with Abell 545 (as we will confirm with this paper), the star pile may have significance in several respects. First, there is the question of its formation. Can tidal debris in a very dense environment settle towards the cluster center? Is this enlightening for the formation of cD halos? Then there is the possibility that such a structure may be used as a

<sup>★</sup> Based on observations obtained at the Gemini Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under a cooperative agreement with the NSF on behalf of the Gemini partnership: the National Science Foundation (United States), the Science and Technology Facilities Council (UK), the National Research Council (Canada), CONICYT (Chile), the Australian Research Council (Australia), CNPq (Brazil) and CONICET (Argentina). Also based on observations taken at the European Southern Observatory, Cerro Paranal, Chile; ESO program 70.B-440(A).



**Fig. 1.** The image is an archival VLT image (see text) and shows the central region of Abell 545. North is up, East to the left. The position of our long slit is indicated. The star pile is visible as the diffuse elongated structure with three faint embedded sources (g1-g3). Note the bright star which complicates the photometric analysis. Two galaxies (SGH1, 2) are marked for which Schneider et al. (1983) already had given radial velocities.

probe for the dark matter profile or even for the very existence of dark matter. The CDM paradigm predicts very dense and cuspy dark matter profiles. These cuspy profiles have however not been found in low luminosity spiral galaxies, nor in dwarf galaxies (e.g. Gentile et al. 2004; Simon et al. 2005; Kuzio de Naray et al. 2006; Gilmore et al. 2007).

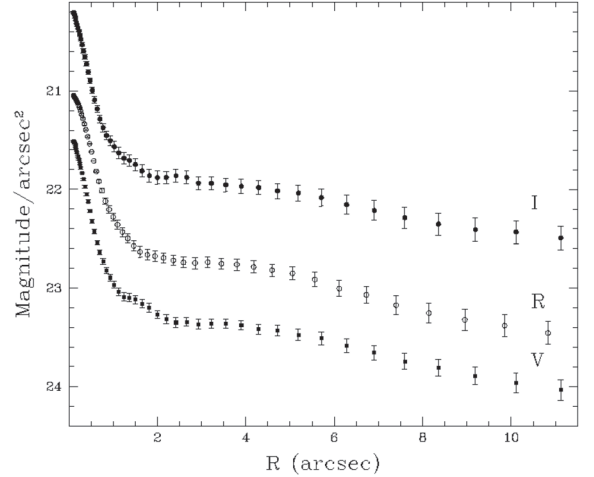
The centers of rich galaxy clusters should be the sites of the highest dark matter densities in the Universe, but are normally dominated by the baryons of a central cD-galaxy. A very faint baryonic structure such as the star pile might offer the possibility of distinguishing between dark matter and alternatives, such as MOND (Sanders & McGaugh 2002). While this will be a challenging observational task for the future, the present data are interesting enough to call the community’s attention to this extraordinary object.

In this contribution we present preliminary measurements of spectroscopic and photometric properties of the star pile in Abell 545, which may provide new insights to its origin. We assume throughout this paper a cosmology with  $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ,  $\Omega_M = 0.3$  and  $\Omega_\Lambda = 0.7$ . This gives a distance modulus of  $m - M = 39.3$ .

## 2. Observations and analysis

### 2.1. Optical imaging

The photometric data consist of 3 images in Bessell  $V, R, I$  taken in the photometric night 3/11/2002 and retrieved from the archive of the Very Large Telescope (VLT) of the European Southern Observatory (programme 70.B-440(A), PI L. Campusano), Cerro Paranal, Chile. The instrument was FORS1. The exposure time for all three images was 460 s. The image seeing values are  $0.5''$ ,  $0.59''$ ,  $0.55''$  for  $V, R, I$ , respectively.



**Fig. 2.** This graph shows the azimuthally averaged surface brightness profiles of the central galaxy plus the star pile in the bands Bessell  $V, R, I$ . At larger radii, the nearby bright star starts to dominate. At the distance of A 545, one arcsec corresponds to 2.64 kpc.

Even though flatfielding using both sky-flats taken the same night and “master” sky-flats provided by the observatory was applied, a still noticeable gradient in the sky background remained. In order to minimize its effect in the photometry, we determined the sky background in different blank sky areas “close” ( $\sim 1$  arcmin) to the star pile, but well outside its apparent projected outer radius. Therefore we assume the uncertainty of our sky determination to be about 1%, which enters the uncertainties of the surface brightness profiles.

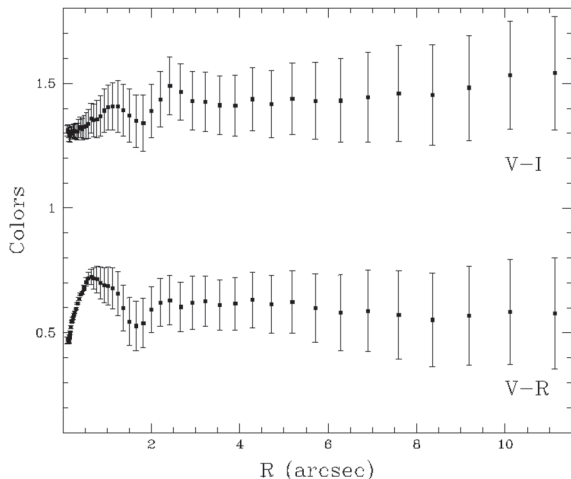
Better than on POSS-plates, the morphology of the star pile is discernable on these VLT images (Fig. 1). One sees a diffuse elliptical structure in which three faint sources are apparently embedded (already known to Struble from Schombert’s CCD-image), the middle one quite precisely in the geometrical center.

The surface brightness profiles of the star pile in the bands  $V, R, I$ , derived from the archival images, were obtained using the ELLIPSE package under IRAF, are shown in Fig. 2. Spikes from the nearby bright star and the two neighbouring galaxies near the central one have been masked. The absolute photometric calibration uses five stars from a standard field observed the same night. The calibration equations obtained using PHOTCAL are:

$$\begin{aligned} v &= V - 27.43(\pm 0.03) - 0.039(\pm 0.035)(V - I) + 0.12X \\ r &= R - 27.34(\pm 0.03) + 0.021(\pm 0.065)(V - R) + 0.078X \\ i &= I - 26.52(\pm 0.04) + 0.043(\pm 0.038)(V - I) + 0.039X \end{aligned}$$

with rms values of 0.03, 0.03 and 0.04, respectively, and where the extinction coefficients were obtained from the Paranal website.

The apparent magnitudes of the three embedded sources, measured through an aperture of 1 arcsec, are  $V_{g1} = 20.8$ ,  $V_{g2} = 21.9$ ,  $V_{g3} = 22.4$ . These numbers should be taken with caution, since the sky determination is complicated by the star pile in which they are embedded. Nevertheless, the absolute magnitudes resemble dwarf elliptical galaxies, although if they are considered as nuclei, their absolute magnitudes should have been much brighter in the past. The colours are equal for all three objects:  $V - R = 0.7$  and  $V - I = 1.3$ . We adopt an absorption of 0.52 in  $V$ , and reddenings  $E(V - R) = 0.1$ , and  $E(V - I) = 0.2$  (Schlegel et al. 1998). That would let the colours be consistent with those of elliptical galaxies within the uncertainties.



**Fig. 3.** Colour profiles in Bessell  $V - R$  and  $V - I$  along the star pile's major axis. The innermost colour gradient is an effect of the different seeing of the images. One arcsec corresponds to 2.64 kpc.

Figure 2 shows that the transition of the profile of the central object occurs quite abruptly, which may be a morphological hint that the central galaxy and the star pile are not associated. From Fig. 3 one cannot derive convincingly a colour difference between the central object and the star pile and consequently also not between the other objects and the star pile.

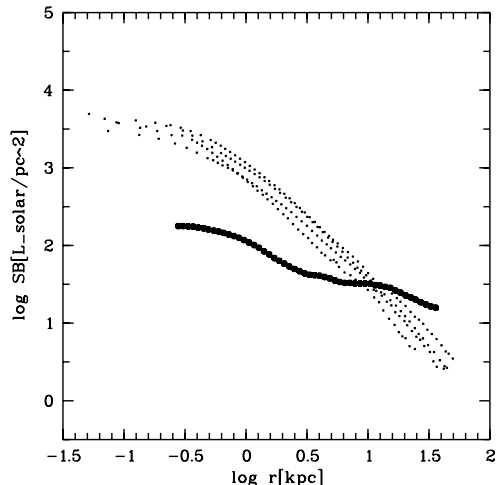
Adopting a luminosity distance of 730 Mpc and an angular distance of 545 Mpc, we transform the surface brightness profile into linear units of  $L_{V,\odot}/\text{pc}^2$ . To correct approximately for the restframe, we further apply a factor  $(1+z)^{-2} = 0.75$ . The results are shown in Fig. 4 together with the profiles of four cD galaxies from Jordán et al. (2004). It becomes very clear that the star pile is something different than a cD halo. The profile is so shallow that also if the uncertainty of the sky level is taken into account, a typical cD power-law profile is excluded. An excellent analytical description (without the claim for physical significance) for the profile is

$$L_{V,\odot}/\text{pc}^2 = 154 \cdot (1 + (r/1.32)^2)^{-1.5} + 34.4 \cdot (1 + (r/38.9)^2)^{-1.5}$$

where  $r$  is in kpc.

Integrating this profile out to 30 kpc results in  $M_V \sim -22.5$ , resembling a giant elliptical, but somewhat fainter than luminous cD-galaxies. The associated dynamical time, adopting  $M/L_V = 8$ , is, within 30 kpc,  $1.6 \times 10^8$  years.

Source g1 in Fig. 1 is worth a particular remark. Colours of  $V - R = 0.7$  and  $V - I = 1.3$  resemble an early type galaxy. We used ISHAPE (Larsen 1999) on the  $V$ -image (which has the best seeing) to find out whether it is resolved. A King profile with a concentration parameter  $c = 100$ , seems to be the best representation. It returns an effective radius of only 0.8 pixels, corresponding to about 400 pc. With an absolute magnitude of  $M_V = -18$  this source would resemble the very rare class of M 32-like dwarf ellipticals, of which only a few representatives are known (Mieske et al. 2004; Chilingarian et al. 2007). However, given that the resolution only is marginal and that it may be influenced by the underlying star pile, we cannot exclude with certainty that it is a projected star, having by coincidence similar colours as the star pile. Sources g2 and g3 have effective radii of 1.55 kpc and 3.2 kpc, respectively.



**Fig. 4.** Comparison between the surface brightness profiles of the star pile and those of four cD galaxies (Jordán et al. 2004) in units of  $L_{\odot}/\text{pc}^2$  vs. kpc. Note that because of the logarithmic scale, the major part of the star pile is in fact the central object and heavily influenced by the seeing. The very shallow profile makes the star pile appear very different from the power-law cD galaxies.

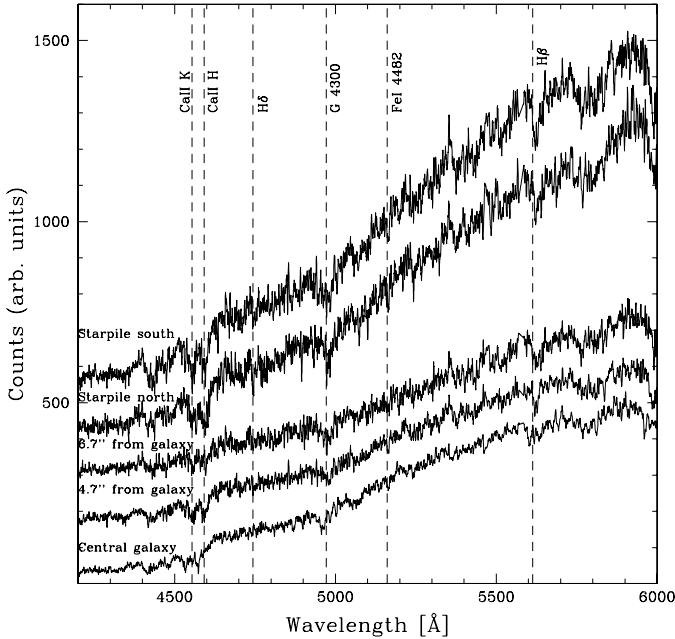
## 2.2. Long-slit spectroscopy

The observations were carried out at Gemini South, Cerro Pachon, Chile, during the nights 19/22/29-11-2006, 25/27-12-2006, and 20/21-1-2007 (programme GS-2006B-Q-69) in queue mode. The instrument was the Gemini Multi Object Spectrograph (GMOS-S). Several long-slit spectra of the star pile were obtained along its major axis as indicated in Fig. 1. A total of  $3 \times 2000$  s exposure time with central wavelength  $5000 \text{ \AA}$  plus  $3 \times 1980$  s with central wavelength  $4900 \text{ \AA}$  exposure was taken giving a total of 3.3 hours exposure on-source. The grating B600+\_G5323 was used which provides a dispersion of  $0.45 \text{ \AA}/\text{pixel}$ . Since the star pile feature has such low surface brightness we chose a slit width of 2.0 arcsec to collect more light, which however degraded the  $FWHM$  of the arc lines to  $\sim 9.5 \text{ \AA}$ . To improve  $S/N$ , but not degrade the spectral resolution, a spatial binning of  $\times 4$  was applied. The spectra cover the range  $3700\text{--}6400 \text{ \AA}$ .

The reduction of the spectra was done using the Gemini IRAF<sup>1</sup> package (v1.9.1). Basic reduction (bias, flat fielding) was done in the standard way. The wavelength calibration was done with the standard Cu-Ar arc, using GSWAVELENGTH, and left residuals with an rms-value of  $\sim 0.3 \text{ \AA}$ . The 2D spectra sharing the same central wavelength were combined using GEMCOMBINE. These combined frames have been sky-subtracted interactively, taking the sky at both sides of the star pile to avoid spatial sky variations and at a distance of about  $1'$ . Then the spectra were extracted and combined.

Figure 5 shows the spectra extracted at different distances from the central object (g2). The lowest spectrum is that of g2 itself and has the usual appearance of an early-type galaxy. Radial velocities were obtained using both identification of lines (using the `rvidlines` task) and cross-correlation (using `fxcor`). In the

<sup>1</sup> IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.



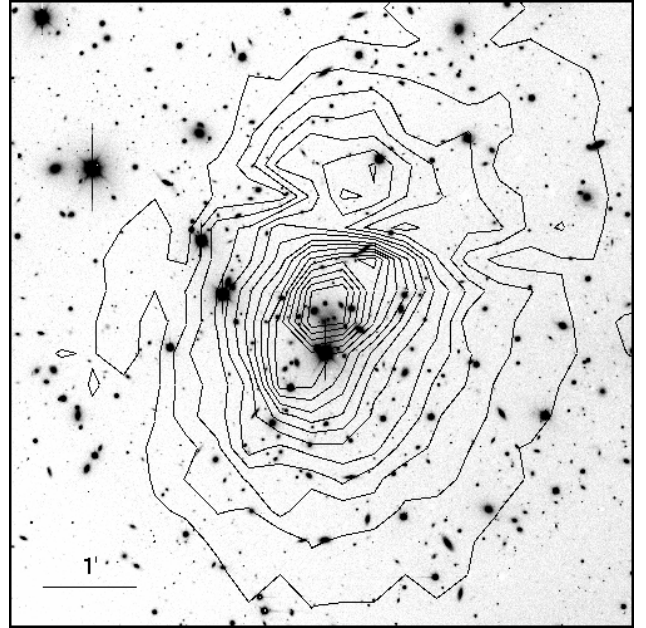
**Fig. 5.** Spectra are shown of the central object and the star pile at two radii from the central galaxy as indicated in the figure. The uppermost two spectra of the star pile have been extracted over an extended radial range north and south of the central object. The spectra are smoothed by a median of 5 pixels. The star pile has a velocity about  $1300 \text{ km s}^{-1}$  higher than the central galaxy. Dashed lines indicate the positions of some spectral features in the star pile.

latter case we used K0III stars from the ELODIE stellar library<sup>2</sup> as radial velocity templates. The heliocentric radial velocity of the star pile is  $47\,100 \pm 60 \text{ km s}^{-1}$ , the uncertainty resulting from the measurements of 16 well identifiable lines. That corresponds to  $z = 0.157$ , thus confirming that the star pile is indeed associated with Abell 545.

However, a striking feature is that the star pile has a velocity of about  $1300 \pm 80 \text{ km s}^{-1}$  larger than the central object. No velocity differences among the spectra of the star pile itself can be seen. The spectra of both the central galaxy and the star pile are too noisy to sensibly measure line strengths, but the relatively weak Balmer lines indicate an old and metal-rich population. The absence of a noticeable  $3727 \text{ Å}$  emission line supports this in that there is no star formation apparent. Unfortunately, little can be said about the outermost spectrum.

### 2.3. X-ray observations

Although Struble (1988) determined the position of the star pile as being “near” the center of Abell 545 through galaxy counting, more precise information is of utter importance to unveil the origin of this feature. We have retrieved an X-ray image of the cluster in the 0.5–2.0 KeV band from the XMM-Newton Science Archive (PI: G. Madejski). Since at this stage we are only interested in the location of the center of the cluster we simply generated a contour level plot, which is seen superimposed to the FORS1 V-image in Fig. 6. The image shows that the star pile is located in the center of the cluster. The elongation of the contour levels have already been detected on previous ROSAT images, and it may be an indication of dynamical youth of the gas distribution (Buote & Tsai 1996). Obviously a proper treatment of



**Fig. 6.** X-ray contour levels superimposed on the FORS1 V image of the center of Abell 545. The star pile clearly lies at the center of the cluster.

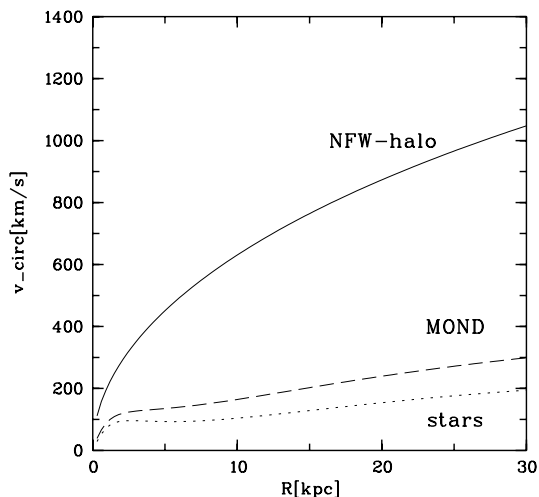
this data would reveal more clues on the formation of the star pile, and it will be included in a future paper.

### 3. Discussion

Schneider et al. (1983) quote radial velocities for two of the galaxies marked in Fig. 1. The velocity for SGH1 is  $46\,200 \text{ km s}^{-1}$ , for SGH2  $48\,360 \text{ km s}^{-1}$ . That means a difference between SGH2 and our central galaxy of  $2600 \text{ km s}^{-1}$ , a value not uncommon for clusters as massive as this one (Czoske 2004). The star pile’s velocity ( $47\,100 \text{ km s}^{-1}$ ) is between these values, consistent with its central position in the cluster. However, it is unknown, whether the star pile really is at rest at the dynamical center. Some other cases have been found where the central cD galaxy has a significant peculiar velocity with respect to the host cluster’s rest frame, the largest one so far being  $600 \text{ km s}^{-1}$  (Pimblet et al. 2006). The radial velocity offset of  $1300 \text{ km s}^{-1}$  between the star pile and the central galaxy implies an even larger three dimensional velocity difference. The central velocity dispersions of massive clusters are of the order  $1000\text{--}1500 \text{ km s}^{-1}$ . Thus, unless the star pile itself has a comparable velocity in the cluster’s restframe, the central galaxy should have achieved its velocity by travelling through a significant part of the cluster potential. In that case, the spatial association with the star pile is plausible, but the dynamical association is doubtful.

Many cD galaxies are known to have multiple nuclei (Gregorini et al. 1994; Laine et al. 2003). Perhaps we are witnessing an unusual case of galactic cannibalism where strong tidal forces disrupted larger galaxies, leaving only the dense nuclei intact (e.g. Gregg & West 1998; Bekki et al. 2001; Cypriano et al. 2006), or where totally disrupted dwarf galaxies have become part of the intracluster medium (López-Cruz et al. 1997; Pracy et al. 2004). There is also the possibility that multiple nuclei are transient phenomena (Merritt 1984; Smith 1985). A scenario in which three or more elliptical galaxies interacted tidally, leaving the star pile as tidal debris and are now visible as the two

<sup>2</sup> [http://www.obs.u-bordeaux1.fr/m2a/soubiran/elodie\\_library.html](http://www.obs.u-bordeaux1.fr/m2a/soubiran/elodie_library.html)



**Fig. 7.** This graph shows three hypothetical circular velocity curves for the star pile. The lowest curve refers to the stellar population only, the middle one assumes MOND and the uppermost an NFW-halo with parameters as given in the text.

or three “nuclei” is perhaps imaginable, but must wait further data to get support.

Although Rines et al. (2007) recently have discovered a similar “star pile” at a larger redshift in the cluster CL0958+4702, that kind of event is unlikely to be the progenitor of the star pile in Abell 545, since the galaxies interacting in CL0958+4702 would rapidly ( $\sim 1$  Gyr) evolve into a single brightest cluster galaxy (BCG) that is not seen in A545. The key difference between both cases might be the mass of the cluster (A545 is more massive), and hence the velocity dispersion. In extremely massive clusters the formation of a BCG might be prevented due to the total disruption of the interacting galaxies.

As Fig. 4 shows, the difference between the shallow profile of the star pile and that of cD-galaxies is striking. Often, cD galaxies are characterized as “normal” galaxies with an additional cD-halo which is manifest by the deviation from a de Vaucouleur profile. But apparently, their profiles can be better described by power laws with an exponent near  $-3$ , in which case the cD-halo is not identifiable as a distinct morphological entity. This is so for NGC 1399 (Dirsch et al. 2003), NGC 6166 (Kelson et al. 2002) and also for the four galaxies in Fig. 4. It is interesting that we can also fit the profile of the star pile by such a power law, but with a core of the size of its visible extension. So one may ask, whether the star pile is only the brightest part of a much more extended structure. In that case it should be dynamically at rest, at the center of the cluster. A significant non-zero velocity in the cluster’s rest frame would disprove this possibility immediately.

Finally, we point out an interesting possibility of using the star pile in Abell 545 to trace the dark matter distribution in the center of a massive galaxy cluster as a test of the standard CDM paradigm. One of the predictions of the CDM paradigm is that dark matter halos should develop cuspy central density profiles. Sites with a high ratio of dark matter density to baryonic density are for example low surface brightness galaxies, where, however, these cuspy profiles have not been found (e.g. Gentile et al. 2004). Instead, the dynamics seem to be consistent with Modified Newtonian Dynamics (Gentile et al. 2007). The centers of massive galaxy clusters should exhibit the highest dark matter densities in the Universe, but if there is a stellar tracer population then it is usually a massive cD galaxy which then

baryonically dominates the total density. The star pile, if it is at the dynamical center, has a low central density, much more suitable for tracing the dark matter. This, of course, is only viable if the star pile is in equilibrium. X-ray studies are in principle equally suited, but departures from hydrostatic equilibrium are probably most pronounced near the very center of a galaxy cluster (Ciotti & Pellegrini 2004; Diehl & Statler 2007).

We illustrate a possible situation in Fig. 7, where we draw the expected circular velocities for the different components. The uppermost curve describes an NFW-halo with a characteristic radius of 300 kpc and a mass of  $1.6 \times 10^{15} M_{\odot}$ . We motivate this mass for Abell 545 by applying the relation between total X-ray luminosity and galaxy cluster mass of Stanek et al. (2006) and an X-ray luminosity of  $3.5 \times 10^{44}$  erg/s, quoted by Böhringer et al. (2004).

The lowest curve represents the star pile after deprojecting the profile of Fig. 2 and assigning an  $M/L_V$ -value of 7. The observable projected velocity dispersions will be somewhat lower, but since the shallow profile enhances the projected dispersion with respect to a “normal” power-law galaxy, it should be less than a factor of about 1.5. Although it will be difficult to measure a velocity dispersion profile for such a faint structure, it is not impossible.

## 4. Conclusions

The star pile belongs to Abell 545 and is located in the center of the cluster. The spectrum indicates an old, probably metal-rich population, which would suggest an origin from tidal debris rather than from primordial intergalactic material. The central object is dynamically decoupled and probably does not play the role of a nucleus in a cD-halo. The surface brightness profile is much too shallow to represent a cD galaxy, although the total brightness of the star pile is of the order of what one would expect for a giant elliptical. A possible scenario is that the three embedded sources interacted tidally, leaving the star pile as tidal debris. More insight into this remarkable object must come from high S/N-spectra of the star pile in combination with a dynamical analysis of the cluster.

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*Note added in proof.* With new Gemini-GMOS spectroscopy we confirm the object called “g1” in the paper as a member galaxy of A 545 and not a projected star.

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