The architecture of Abell 1386 and its relationship to the Sloan Great Wall

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ABSTRACT

We present new radial velocities from AAOmega on the Anglo-Australian Telescope for 307 galaxies (b_J < 19.5) in the region of the rich cluster Abell 1386. Consistent with other studies of galaxy clusters that constitute subunits of superstructures, we find that the velocity distribution of A1386 is very broad (21 000–42 000 km s^{-1}, or z = 0.08–0.14) and complex. The mean redshift of the cluster that Abell designated as number 1386 is found to be ~0.104. However, we find that it consists of various superpositions of line-of-sight components. We investigate the reality of each component by testing for substructure and searching for giant elliptical galaxies in each and show that A1386 is made up of at least four significant clusters or groups along the line of sight whose global parameters we detail. Peculiar velocities of brightest galaxies for each of the groups are computed and found to be different from previous works, largely due to the complexity of the sky area and the depth of analysis performed in the present work. We also analyse A1386 in the context of its parent superclusters: Leo A and especially the Sloan Great Wall. Although the new clusters may be moving towards mass concentrations in the Sloan Great Wall or beyond, many are most likely not yet physically bound to it.

Key words: catalogues – galaxies: clusters: individual: Abell 1386 – galaxies: distances and redshifts – galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – large-scale structure of Universe.

1 INTRODUCTION

Galaxies are typically found clustered together with other galaxies – whether this be in small groups or large rich galaxy clusters that contain ~10^{11} members. In turn, these objects can be clustered together into superclusters and joined in a complex manner via filaments of galaxies to form the now familiar web-like or sponge-like structure (Gott, Dickinson & Melott 1986) seen in modern redshift surveys (e.g. Colless et al. 2001). Amongst the first systematic redshift slice surveys in the early 1980s was the CfA2 survey. The survey revealed evidence for the so-called ‘Great Wall’ (de Lapparent, Geller & Huchra 1986; Geller & Huchra 1989; Ramella, Geller & Huchra 1992). This structure was found to extend over 100° in the sky, passing from A779 in the west and through the Coma and A1367 galaxy clusters up to A2199 at its eastern end, thus having a physical size of ~160 h_{70}^{-1} Mpc. Although more large-scale filaments have been noted in the literature since the discovery of the Great Wall (e.g. Pimbblet, Drinkwater & Hawkrigg 2004; Bharadwaj, Bhavsar & Sheth 2004; Porter & Raychaudhury 2005), the largest known (local) structure to date is the Sloan Great Wall (SGW; Tegmark et al. 2004; Gott et al. 2005; Nichol et al. 2006; Einasto et al. 2010) which is 80 per cent longer than the CfA2 Great Wall. Finding and refining our knowledge about very large structure in the Universe alongside contrasting them with predictions from a variety of structure formation scenarios is highly beneficial to a number of areas of extragalactic research ranging from determining the homogeneity scale to testing whether our dark matter description of the evolution and topology of structure in the Universe is correct (cf. White et al. 1987; Park 1990; Hara & Miyoshi 1993; Pimbblet et al. 2004; Gott et al. 2008; Yaryura, Baugh & Angulo 2010). Over the past few years, we have been actively compiling redshift data for over 1000 Abell clusters with the aim of calculating the peculiar velocities of their brightest cluster members (BCM; Pimbblet, Roseboom & Doyle 2006; Pimbblet 2008; Coziol et al. 2009). A1386 drew our attention during this compilation effort as it was the only cluster in this sample of ~1200 clusters for which a BCM could be identified whose radial velocity coincided with one of each of the three subunits identified along

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the line of sight (Coziol et al. 2009). The lowest redshift BCM (2MASX J11481434−0159000) turned out to have a very high peculiar velocity just above the cluster’s radial velocity dispersion of ∼1180 km s$^{-1}$. Thus A1386 was included as one of several target clusters with BCMs of both low and high peculiar velocities in order to study possible relations of cluster substructure with BCM peculiar velocity. As it happens, A1386 is also a member of the Leo A supercluster (SCL100 in Einasto et al. 1997; cf. Pimbblet, Edge & Couch 2005) which itself is part of the even larger SGW (Gott et al. 2005; Einasto et al. 2010). Therefore, a deep redshift survey of its surroundings appeared to offer new insights into the structure and depth of such large aggregates of galaxy clusters.

In this paper, we present new observations of A1386 taken with AAOmega on the Anglo-Australian Telescope. In Section 2, we describe these observations in detail, including the galaxy selection and completeness. We examine the robustness of our new radial velocities in Section 3. In Section 4, we present a full analysis of the dynamics of A1386 and other objects along the line of sight to provide a better understanding of the state of this unusual cluster. In Section 5, we consider this cluster in the context of the SGW. We summarize our findings in Section 6 and present our new radial velocities in the Appendix A. Throughout this paper, we use $H_0 = 75 \, \text{h}_{75} \, \text{km s}^{-1} \, \text{Mpc}^{-1}$, $\Omega_M = 0.27$ and $\Omega_{\text{vacuum}} = 0.73$.

2 DATA AND REDUCTION

The observations for this work are from AAOmega two degree field (2dF) multi-fibre spectroscopy at the Anglo-Australian Telescope, Australia. AAOmega is the 2006 upgrade to the 2dF spectrograph (Lewis et al. 2002). Unlike 2dF, AAOmega is a dual-beam spectrograph that is able to cover a wavelength range of 3700–8500 Å. Similar to its predecessor, AAOmega can achieve the simultaneous observation of up to ∼400 targets (including guide stars) in any single configuration (see www.aao.gov.au/AAO/2df/aaomega/aaomega.html).

Our observations were made in a mixture of conditions. For our first set of observations taken on 2007 March 25, thick cloud and fog spoiled the spectra of all targets. On the second night, the seeing was large (2.5 arcsec), but otherwise the conditions were ideal (i.e. photometric). Here we elect only to use the observations from 2007 March 26 and discard the weather-affected observations.

The targets for our observations are chosen in a similar manner to Pimbblet et al. (2006). In brief, we make use of the Automated Plate Measuring Machine (APM) catalogue (e.g. Maddox et al. 1990; see also www.ast.cam.ac.uk/~mike/apmcat/) to select all objects flagged as galaxies in both $b_J$ and $r_J$ passbands, in order to create a sample that will not be highly contaminated by Galactic stars and not biased with regard to galaxy colour (i.e. we do not just select elliptical galaxies that lay on the colour–magnitude red sequence). The APM positional accuracy is better than 0.3 arcsec and is therefore more than sufficient for AAOmega observations. Moreover, this approach is the same approach used by Colless et al. (2001) for the Two Degree Field Galaxy Redshift Survey (2dFGRS), being more complete for fainter galaxies. Targets were chosen within a box of $−2:7 < \text{Dec.} < −1:2$ and $176:3 < \text{RA} < 177:8$ (equinox J2000).

In making the AAOmega observing configuration, we assigned a priority to each target galaxy based upon its $r_J$ magnitude such that the highest priority is given to the brightest galaxies. This was done not only to obtain the best possible magnitude-limited sample of galaxies, but also to alleviate any possible effect from poor weather or fibre positioning, as brighter galaxies are more likely to generate good-quality spectra. We did not perform any down-weighting of targets when these had literature redshifts. Guide star candidates were also generated from the APM catalogue in the magnitude range $13.75 < r_J < 14.25$ and were quality-controlled (by eye) to ensure that they were isolated. Blank sky positions were provided by the software and down-selected so that none of them was accidentally placed on top of ‘real’ objects and spoiled our sky subtraction.

In Fig. 1, we plot all the observed galaxies out of the total possible number of potential targets as a function of magnitude, down to the limit of $b_J = 19.5$. All of the brighter galaxies ($b_J < 14.5$) were observed successfully, with the fraction falling to less than 80 per cent at $b_J = 19.5$. The dip in fraction observed in the region of $b_J \sim 15$ and some of the fall towards fainter targets is due to one of two effects: (1) there is a fibre crossing the target in order to hit a brighter (i.e. higher priority) target or (2) the target is in close proximity to another target of equal or higher priority which would cause a fibre collision should both targets be observed. At fainter magnitudes, there are not enough fibres left to be placed on all possible targets, and hence many of them simply do not get observed.

Our observations used the 580V and 385R gratings which yield a central dispersion of 1.0 and 1.6 Å pixel$^{-1}$, respectively. These AAOmega spectra are generally superior in quality to the 2dFGRS survey (Colless et al. 2001) given both the higher spectral resolution and coverage of a wider wavelength range, and are generally well able to yield secure redshifts despite the somewhat inclement observing conditions.

Our data set was reduced with the 2dF data reduction pipeline in a standard manner (see www.aao.gov.au/2df/). This included a Laplacian edge detection step to reject cosmic rays from our data in an efficient manner (see Farage & Pimbblet 2005, and references therein for a full discussion of the benefits of this methodology). To obtain redshifts of our targets, we made use of the zcode package that was originally employed on 2dFGRS by Colless et al. (2001), and we refer the reader to that publication for more explicit details. The output of the code consists of a cross-correlation with the
best-matched template spectra, i.e. those with the highest $R$ value according to Tonry & Davis (1979). Our template spectra range from G stars, through globular clusters, right out to galaxy spectra. Each redshifted target was then de-redshifted to rest-frame wavelengths and checked by eye (by KAP) to ensure that the emission and absorption features are in the correct locations. The fraction of our targets that produce reliable redshifts is high: 87 per cent of all our targets ($100\,\text{per cent for } b_J < 15.0$, only dropping below 80 per cent at $b_J > 19.25$). We present our redshift catalogue in Appendix A.

3 REDSHIFTS AND RELIABILITY CONTROL

In total, we obtained redshifts for 307 objects. Of these, three are most likely stellar in nature as they have velocities of less than $200\,\text{km s}^{-1}$. One of them (PRA003) is SDSS J114948.77–014728.2, already suggested to be a star in the Sloan Digital Sky Survey (SDSS) data base (Abazajian et al. 2009, and references therein), and two others (PRA096 and 244) had radial velocities measured in 2dFGRS suggesting them to be stars.

To further probe the reliability of our redshift measurements, we proceed by comparing our redshifts to those already published in the literature. For this comparison, we make use of a number of other catalogues that possess an overlap with our own observations: 2dFGRS (Colless et al. 2003); 2QZ (Croom et al. 2004); 6dFGS (Jones et al. 2009); SDSS Data Release 7 (DR7; Abazajian et al. 2009); da Costa et al. (1998), Doyle et al. (2005), Falco et al. (1999), Grogin, Geller & Huchra (1998), Quintana & Ramírez (1995), Shectman et al. (1996), Slinglend et al. (1998) and Theureau et al. (2005). In some cases, a target in our catalogue appears in several of the above catalogues, each with a different reported redshift. In Fig. 2, we plot the difference between our measured redshifts and the literature redshifts. The measured mean and median difference in redshift is $-23$ and $27\,\text{km s}^{-1}$, respectively. When performing this analysis, we found two especially noteworthy, low-redshift ($z < 0.15$), discrepancies between our redshifts and previously published ones, which exceed by far the quoted redshift errors. The first major difference is between our results and 6dFGS (PRA284; Appendix A) – this is due to a poor-quality 6dFGS spectrum (Jones, private communication). The second is PRA037 (also 2MASX J11481434–0159000; Appendix A) when compared to Quintana & Ramírez (1995). This galaxy also has published redshifts in three other catalogues. Whilst our redshift is non-discrepant with both 2dFGRS (Colless et al. 2003) and 6dF (Jones et al. 2009), it is $2.6\sigma$ away from that published in SDSS-DR2 (Abazajian et al. 2004). The reason for the discrepancy becomes more obvious from an examination of this object’s image at optical (i.e. the Digitized Sky Survey and SDSS) and near-infrared (i.e. 2MASS) wavelengths: it possesses a secondary core or neighbour galaxy 6-arcsec away at PA $\sim 230^\circ$. We therefore contend Quintana & Ramírez (1995) on the one hand, and SDSS-DR2, 2dFGRS and 6dF on the other, each measured a different core’s velocity.

4 ANALYSIS

4.1 Dynamics

We begin our analysis of the dynamics and architecture of A1386 by examining its velocity structure. In constructing the velocity histogram (Fig. 3), we include not only the objects from our new observations, but also all objects with redshifts available from the literature (see Section 3 above and Appendix A). Measurements that belong to the same galaxy were identified, based on their close positional coincidence, and the velocity with smallest error was chosen for that galaxy.

The velocity distribution (Fig. 3) is unusually broad, with several subpeaks, and there appears to be rich and highly complex substructure in the core of A1386. The complexity is perhaps not unexpected given that A1386 resides within the supercluster Leo A (SCL100 in Einasto et al. 1997; cf. Pimbblet, Edge & Couch 2005) and hence is a part of the SGW (see Fig. 9 of Gott et al. 2005). We note that...
this broad peak in velocity is, however, distinct and isolated from other foreground and background structures. Indeed, this cluster is very isolated in redshift space: the closest cluster in redshift space is WBL 355 at $z \sim 0.028$ (White et al. 1999), some 52 arcmin due WNW from the centre of A1386. We refrain from making further analysis of WBL 355 as our observations are only just probing the outskirts of this poor cluster.

We note that the redshift of A1386 ($z = 0.1018$) given by Struble & Rood (1999) is based on that of a single galaxy (published by Quintana & Ramirez 1995) whose redshift is coincidently located near the middle of the velocity distribution. However, it presents a real problem in trying to compute any ‘mean’ redshift of the population, let alone a meaningful velocity dispersion (cf. Abell 779 in Oegerle & Hill 2001). This can readily be illustrated by a simple application of the $3\sigma$ clipping technique of Yahil & Vidal (1977) where the mean velocity and dispersion of a cluster are determined by iteratively clipping any galaxy that is greater than $3\sigma$ from the mean of the velocity distribution. Using an initial clip of $21\;000 < cz < 42\;000\;\text{km}\;\text{s}^{-1}$, we obtain a mean velocity of $31241 \pm 275\;\text{km}\;\text{s}^{-1}$ and an unphysically large (and clearly erroneous) velocity dispersion of $5723\;\text{km}\;\text{s}^{-1}$. We are thus forced to split up the cluster into more sensibly sized subcomponents. Fig. 3 would suggest that there are multiple subpeaks in the overall velocity distribution, and therefore we proceed with the aim of attempting to isolate these peaks.

### 4.2 Substructure

Based on an inspection of Fig. 3, it is likely that A1386 has at least four components (mean velocities of approximately 25 000, 28 500, 31 000 and 37 000 km s$^{-1}$; see Fig. 3) that make up what Abell (1958) originally defined as the cluster proper. In order to better delineate the structure of the cluster, we now apply the Dressler & Shectman (1988, hereafter DS) test to our catalogue – one of the most sensitive general tests for substructure available (Pinkney et al. 1996; see also Section 4.4). For each cluster member, the DS algorithm computes the mean local velocity, $v_{\text{local}}$, and local standard deviation, $\sigma_{\text{local}}$, of that member’s $N_{\text{local}}$ nearest neighbours in projection. These localized values are then compared to the global cluster mean velocity, $\bar{v}$, and the cluster velocity standard deviation, $\sigma_{\text{cluster}}$, to produce a measure of deviation:

$$\delta^2 = \left(\frac{N_{\text{local}} + 1}{\sigma_{\text{cluster}}^2}\right) \left[ (\bar{v}_{\text{local}} - \bar{v})^2 + (\sigma_{\text{local}} - \sigma_{\text{cluster}})^2 \right]$$

that can be utilized to locate clumps of spatially close deviant galaxies. Consistent with DS, in this work we use the 10 nearest neighbours (i.e. $N_{\text{local}} + 1 = 11$) to compute $\delta$. A cumulative quantity, $\Delta$, is then found by summing all values of $\delta$ for the cluster. By comparing $\Delta$ to Monte Carlo simulations in which the member’s velocities are shuffled around the positions, we can estimate a confidence level for the overall probability of substructure in the cluster.

We acknowledge that we can already guess that the DS test will show that the cluster has substructure – the primary purpose of applying this technique, however, is to specify the sky positions of likely subcomponents within the cluster. Fig. 4 displays the results of applying the DS test to our data – each circle is drawn with a diameter proportional to the deviation of a given galaxy from the global mean velocity (here, assumed to be $31241\;\text{km}\;\text{s}^{-1}$), $\delta_N$ (see DS for full details of the test); hence substructure is interpreted as (spatially close) overlapping circles. We also display the results of the average and most deviant of 1000 Monte Carlo simulations in Fig. 4.

Unsurprisingly, the DS test gives unequivocal evidence for subclustering as the probability of obtaining the cumulative deviation found for the cluster is very low in comparison to the simulations: $P(\Delta) \ll 0.001$.

Interestingly, Fig. 4 displays several regions of overlapping circles in the real data suggesting localized subclustering (Dressler & Shectman 1988). We now ask if any of these regions (or, indeed, any localized regions at all) correspond to any of the individual peaks seen in redshift space (Fig. 3). To do this, we split the cluster catalogue up into six redshift channels that encompass each of the major peaks seen in Fig. 3 and search (by eye) for any obvious spatial overdensities. The result of this search is depicted in Fig. 5.

We believe that the subcomponent marked $\zeta$ is the cluster proper because it is nearest to what Abell (1958) catalogued as the cluster centre. Comparing Fig. 5 to Fig. 4 shows that a number of the other subcomponents (e.g. $\delta$) probably constitute subclusters that are interacting in a complex manner with $\zeta$, and potentially with each other as well.

Of the other overdensities, we suggest that $\theta$ and $\kappa$ are the same entity that extends over two of the redshift channels in Fig. 5. We identify $\theta$ and $\kappa$ as Abell 1373. By limiting the redshift distribution to the range $35\;500 < cz < 42\;000\;\text{km}\;\text{s}^{-1}$ and localizing the spatial extent to $176.3 < RA < 176.6$ and $-2.6 < Dec. < -2.3$, we compute that Abell 1373 has a mean velocity of $38063 \pm 256\;\text{km}\;\text{s}^{-1}$ and a velocity dispersion of $1428^{+228}_{-354}\;\text{km}\;\text{s}^{-1}$ from 31 members. Our values for $\bar{v}$ and $\sigma$ are comparable (i.e. within $3\sigma$) to those computed in the recent study of rotating galaxy clusters by Hwang & Lee (2007) despite using a different spatial extent.

We have also searched the NASA/IPAC Extragalactic Data base (NED; see, nedwww.ipac.caltech.edu) for possible clusters that may correspond to overdensities $\alpha$ through $\kappa$ in order to check whether they were known before. We found reasonable matches with clusters reported by Estrada et al. (2007), Koester et al. (2007), Miller et al. (2005) and Merchán & Zandivarez (2005), and present these in Table 1, along with basic data on the overdensities themselves.

We have approximated the mean velocity of each group by taking all galaxies within the marked circles (radius of 0.15 on the sky; equivalently 1 Mpc at $z = 0.1$) in Fig 5 for the purpose of matching them to the literature. We will refine these values later in this work by undertaking detailed decomposition work using Kaye’s mixture model (KMM). We note that a number of our groups have reasonable matches to known literature clusters ($\alpha$, $\delta$, $\zeta$, $\theta$ and $\kappa$). A further two matches ($\epsilon$ and $\eta$) are found within the MaxBCG catalogue of Koester et al. (2007). Although the MaxBCG photometric cluster redshifts are not quite the same as our spectroscopic cluster redshifts, they are of the order of the quoted photometric redshift error of $\Delta_z = 0.01$ given by Koester et al. (2007) away from our estimates. Therefore, we regard these matches as plausible. Finally, $\theta$ is identified as matching EAD2007 236 (Estrada et al. 2007), which is also based on a photometric redshift. We suggest that EAD2007 236 may be a foreground extension to A1373.

### 4.3 Brightest cluster members

If the subcomponents identified in Fig. 5 truly are subclusters or groups, then when we examine each separately, they may visually resemble such a group. For instance, each subcomponent may contain a BCM that is a giant elliptical or a cD class galaxy with an extended diffuse halo; or we may find several galaxies in the act of merging to form such a galaxy surrounded by an overdensity of early-type galaxies (cf. Bautz & Morgan 1970). Conversely, not finding a cD class galaxy does not immediately mean that we have
Figure 4. Results of the DS test. Top left: spatial distribution of all galaxies with 21 000 km s\(^{-1}\) < \(cz\) < 42 000 km s\(^{-1}\). Top right: result of the DS test as applied to A1386 – spatially close overlapping circles denote likely substructure locations. Bottom left: average of 1000 Monte Carlo simulations. Bottom right: the single most deviant of 1000 Monte Carlo simulations.

not located a cluster. The majority of Abell clusters are of ‘late’ Bautz–Morgan type, i.e. they lack an obvious central, bright and dominant early-type galaxy; here, we are aiming to build up a body of evidence for the most probable subgroups.

In order to perform this test, we inspect SDSS images of the regions centred on the subcomponents. Out of the components identified in Fig. 5, we find that groups \(\alpha\), \(\gamma\), \(\delta\), \(\epsilon\) and \(\zeta\) have obvious bright ellipticals within the regions indicated in Fig. 5. Of these, \(\alpha\), \(\delta\), \(\epsilon\) and \(\zeta\) are all at the correct redshift but the bright elliptical near the \(\gamma\) spatial overdensity is a foreground object. We display these four BCMs in Fig. 6.

The BCM in \(\alpha\) is SDSS J114849.67–022817.6 and was not observed in our sample due to fibre collisions and prioritization at the field configuration stage (the same is true for \(\delta\) and \(\epsilon\)). The redshift of this galaxy from SDSS is \(cz = 25428\) km s\(^{-1}\). We identify the BCMs in \(\delta\) and \(\epsilon\) as SDSS J114542.16–020151.9 (\(cz = 23624\) km s\(^{-1}\)) and SDSS J114805.92–014119.2 (\(cz = 28181\) km s\(^{-1}\)), respectively. Meanwhile, PRA037 is identified as the BCM of \(\zeta\), and SDSS J114814.35–015859.8 (also labelled 2MASX J11481434–0159000), with \(cz = 31022\) km s\(^{-1}\) from our catalogue.

4.4 Results of the KMM algorithm

The DS test is one of the best tests available in a generic 3D case for finding substructure (Pinkney et al. 1996). It is not, however, without its own problems. Although it can be readily sensitive from equal mass mergers down to a 3:1 mass merger ratio, given modest numbers of redshifts (cf. Pinkney et al. 1996; Pimbblet 2008), the number of false positive detections can pose problems. Indeed, it may be that some of the subcomponents outlined above do not represent true infalling groups or subclusters (e.g. \(\beta\); see Fig. 5), given their lack of bright ellipticals. Moreover, false positive detections can be particularly evident for clusters that have features such as significant radial gradients in their velocity dispersion profiles (Pinkney et al. 1996). With a structure such as A1386, the likelihood of false positives may be comparatively high.

To proceed further with delineating the possible subcomponents, we now apply KMM algorithm to the velocity distribution. The KMM algorithm is described in detail in Ashman, Bird & Zepf (1994) and has been used extensively in the literature (e.g. recent examples include Johnston-Hollitt, Hunstead & Corbett 2008; Owers, Couch & Nulsen 2009) for just this purpose. In brief, based...
Figure 5. Spatial distribution of galaxies in redshift channels corresponding to the peaks seen in Fig. 3 (triangles); all other galaxies in the range $21000 < \text{cz} < 42000$ km s$^{-1}$ are plotted as dots. Localized overdensities – i.e. likely cluster subcomponents – are circled and labelled $\alpha$ through $\kappa$.

on a user-supplied number of Gaussians with some initial best guess of their central position, the KMM algorithm effectively partitions the data into a number of sets and evaluates whether the fit that results from these Gaussians is superior to a single Gaussian fit. In all the cases studied in this work, multiple Gaussians are always found to be superior fits to the data than a single Gaussian by the KMM algorithm. The key questions here are what input should the KMM be given: how many Gaussians should one fit to the data and with what initial parameters?

In the 1D case, we elect to try two sets of parameters: the first with four Gaussians and the second with six. The reason for these choices stems from visual inspection of Fig. 3 as discussed above. For each peak in the velocity distribution, we use an approximate guess of the velocity dispersion ($\sigma_v$) from a visual inspection of Fig. 3. We present the input and output parameters for these two scenarios in Table 2.

We conducted several runs of the KMM algorithm to check how sensitive the results are to the initial conditions imposed by
Table 1. Known clusters in the literature with close proximity to the overdensities identified in Fig 5. The mean velocity quoted for each group is computed from galaxies within the marked circles (radius of 0.15) in Fig. 5.

<table>
<thead>
<tr>
<th>Group</th>
<th>RA (J2000)</th>
<th>Dec. (J2000)</th>
<th>$\overline{v}$ (km s$^{-1}$)</th>
<th>NED match</th>
<th>RA (NED)</th>
<th>Dec. (NED)</th>
<th>cz (NED)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>11 49 00</td>
<td>-02 22 36</td>
<td>26 083</td>
<td>SDSS-C4 1121</td>
<td>11 48 51</td>
<td>-02 30 37</td>
<td>26 235</td>
</tr>
<tr>
<td>$\beta$</td>
<td>11 49 38</td>
<td>-01 59 24</td>
<td>23 675</td>
<td>No plausible match found</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\gamma$</td>
<td>11 49 36</td>
<td>-01 24 00</td>
<td>25 177</td>
<td>No plausible match found</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\delta$</td>
<td>11 45 36</td>
<td>-02 06 00</td>
<td>24 343</td>
<td>MZ 07066</td>
<td>11 45 29</td>
<td>-02 06 24</td>
<td>23 769</td>
</tr>
<tr>
<td>$\varepsilon$</td>
<td>11 48 05</td>
<td>-01 42 00</td>
<td>28 243</td>
<td>MaxBCG J177.02469-01.68868</td>
<td>11 48 06</td>
<td>-01 41 19</td>
<td>32 393$^a$</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>11 48 22</td>
<td>-02 00 00</td>
<td>30 813</td>
<td>Abell 1386</td>
<td>11 48 22</td>
<td>-01 56 41</td>
<td>30 519</td>
</tr>
<tr>
<td>$\eta$</td>
<td>11 45 31</td>
<td>-02 01 48</td>
<td>34 408</td>
<td>MaxBCG J176.79744-01.88906$^b$</td>
<td>11 47 11</td>
<td>-01 53 21</td>
<td>30 774$^b$</td>
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<tr>
<td>$\theta$</td>
<td>11 45 46</td>
<td>-01 19 48</td>
<td>36 326</td>
<td>[EAD2007] 236</td>
<td>11 45 52</td>
<td>-02 20 11</td>
<td>34 704$^a$</td>
</tr>
<tr>
<td>$\iota$</td>
<td>11 47 12</td>
<td>-02 24 00</td>
<td>38 975</td>
<td>No plausible match found</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\kappa$</td>
<td>11 45 31</td>
<td>-02 28 12</td>
<td>39 092</td>
<td>Abell 1373</td>
<td>11 45 28</td>
<td>-02 23 40</td>
<td>39 393</td>
</tr>
</tbody>
</table>

$^a$Denotes a photometric cluster redshift estimate.
$^b$It is possible that $\eta$ is a SW extension of $\varepsilon$.

Figure 6. BCMs in the groups identified in Fig. 5. All of them have the correct redshifts to be associated with the groups that they were identified from.
Table 2. Input and output parameters for the 1D application of the KMM algorithm. The table is split into two halves: the upper half shows the result of inputting four Gaussians to the KMM algorithm, whereas the bottom half shows the result of six Gaussians. The final column shows an estimate of the correct allocation rate by KMM for each partition.

<table>
<thead>
<tr>
<th>Group</th>
<th>Input parameters</th>
<th>KMM output</th>
<th>$N_{gal}$</th>
<th>Rate (per cent)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\bar{v}$ (km s$^{-1}$)</td>
<td>$\sigma_v$ (km s$^{-1}$)</td>
<td>$\bar{v}$ (km s$^{-1}$)</td>
<td>$\sigma_v$ (km s$^{-1}$)</td>
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<td>818</td>
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<td>39 500</td>
<td>1000</td>
<td>39 442</td>
<td>1844</td>
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</tbody>
</table>

Figure 7. DS test results of the first redshift peak identified in Table 2. The cross denotes the position assigned to A1386 by Abell (1958). Two major subclusters which contain BCMs ($\alpha$ and $\delta$) can be seen at (RA, Dec.) = (177.3,−2.5) and (176.4,—2.1). We suggest that these are two clusters or groups in their own right.

guessing the Gaussian’s parameters (i.e. $\sigma_v$ and $\bar{v}$). This was done by perturbing both $\sigma_v$ and $\bar{v}$ by incremental amounts. In the cases where the perturbation is modest ($\Delta(\bar{v}) < 500$ km s$^{-1}$ and $\Delta\sigma_v < 0.5\sigma_v$), the KMM algorithm converged on the same solution. Therefore, despite guessing the initial inputs, we regard the output of the KMM algorithm to be reasonably robust.

From Table 2, it appears that a four-Gaussian approach is incorrect. The highest redshift Gaussian (labelled group 4 in Table 2) of the four-Gaussian approach has a very large velocity dispersion of $\sigma_v = 2316$ km s$^{-1}$. We regard this as erroneous since the implied cluster mass would be unphysically high. However, the first three Gaussians are good fits to the data and are highly plausible.

The six-Gaussian solution appears to be superior to the four-Gaussian solution at first glance (Table 2). Effectively, what was group 4 in the four-Gaussian solution has been segmented into three new subcomponents. Of these, group 4 looks to be nearly perfectly partitioned, with groups 5 and 6 both possessing more reasonable parameters than before. Arguably, we could also partition group 6 into two further subcomponents (centred on $\approx 38 000$ and $\approx 40 000$ km s$^{-1}$). But doing so results in very few galaxies ($N_{gal} = 19$) in one partition and a much reduced correct allocation rate (76 per cent) indicated by the KMM algorithm. Hence, we do not regard seven Gaussians as an improvement over the six-Gaussian solution in one dimension.

4.5 Interpretation

Taken together, the above suggests that the galaxy populations of these other clusters have biased the cluster and richness identification made by Abell (1958). There are at least three significant, bona fide subclusters in the field of A1386: these are the first three redshift slices specified in Table 2 (both the four- and six-Gaussian KMM solutions).

Of these, the second and third groupings are fairly solid detections with a single BCM each ($\epsilon$ and $\zeta$; Figs 5 and 6). The first cluster in Table 2 merits further attention given that it has two subclusters ($\alpha$ and $\delta$; Fig. 6) with potential BCMs (Fig. 6), both of which have matches to literature clusters (Table 1). On the face of it, this first subcluster appears to have a velocity dispersion ($\sigma_v = 1088$ km s$^{-1}$) that is typical of a rich, massive galaxy cluster by itself. But given the two BCMs and their spatial separation (Fig. 5; $\approx 2.5$ Abell radii apart), it may be the case that this redshift grouping is a cluster that is undergoing the early to mid-stages of a merger event.

To test this hypothesis, we apply a further DS test, but limit ourselves to only those galaxies contained in the first redshift grouping in Table 2. Given we have 138 galaxies in this redshift slice, we will be sensitive to about a 4:1 mass merger ratio (see Pinkney et al. 1996). The DS test for this redshift slice generates a result of $P(\Delta) < 0.001$ which strongly suggests the presence of substructure.

In Fig. 7, we show the results of the DS test in this redshift slice. From this, it is quite clear that there are two major self-contained subclusters (RA, Dec.) = (177.3,−2.5) and (176.4,—2.1) that dominate this slice. Moreover, these two subclusters, $\alpha$ and $\delta$, are among those in which we identified typical BCMs. It may also be the case that the $\beta$ and $\gamma$ groups (Fig. 5) are groups in their own right as well, but we have not been able to identify dominant BCMs in these regions and they are probably false positives given the small number of redshifts available (cf. Pinkney et al. 1996).

The six-Gaussian solution to the KMM algorithm (lower half of Table 2) suggests that the three slices with the highest redshift may also contain groups or clusters of galaxies in their own right (indeed,
Table 3. Bona fide clusters and groups with dominant BCMs in the field of A1386. N(gal) is the number of galaxies used to derive \( \overline{cz} \) and \( \sigma_v \) and covers the whole field of view for A1386-C and -D, but is spatially limited to the area of the subclusters found in Fig. 7 for A1386-A and -B.

<table>
<thead>
<tr>
<th>Name</th>
<th>N(gal)</th>
<th>( \overline{cz} ) (km s(^{-1}))</th>
<th>( \sigma_v ) (km s(^{-1}))</th>
<th>Other cluster names</th>
<th>BCM (km s(^{-1}))</th>
<th>( v_{pec} )</th>
<th>( v_{pec}/\sigma_v )</th>
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</thead>
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<td>21</td>
<td>23 593 ± 68</td>
<td>310^{+64}_{-59}</td>
<td>MZ 07066</td>
<td>SDSS J114542.16−020151.9 (δ)</td>
<td>−95</td>
<td>−0.43</td>
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<td>32</td>
<td>25 952 ± 83</td>
<td>482^{+73}_{-50}</td>
<td>SDSS-C4 1121</td>
<td>SDSS J114849.67−022817.6 (α)</td>
<td>−297</td>
<td>−0.88</td>
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<tr>
<td>A1386-C</td>
<td>56</td>
<td>28 219 ± 70</td>
<td>451^{+60}_{-42}</td>
<td>MaxBCG J177.02469−01.68686</td>
<td>SDSS J114805.92−014119.2 (ε)</td>
<td>−61</td>
<td>−0.15</td>
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<tr>
<td>A1386-D</td>
<td>66</td>
<td>30 856 ± 99</td>
<td>818^{+81}_{-63}</td>
<td>Abell 1386</td>
<td>SDSS J114814.35−015859.8 (ζ; PRA037)</td>
<td>+108</td>
<td>+0.15</td>
</tr>
</tbody>
</table>

we have already identified A1373 at 38063 km s\(^{-1}\); see above). However, apart from A1373, the lack of BCMs coupled with no high galaxy overdensity suggests otherwise. The simplest interpretation for these three redshift slices is that they are part of some larger scale structure. Indeed, looking at the \( cz > 38,000 \) km s\(^{-1}\) slice in Fig. 5 (which approximately corresponds with the highest redshift slice in Table 2), the galaxies appear to be spread across the sky in the same manner that walls and filaments of galaxies are (cf. Pimbblet et al. 2005).

To summarize, we present the global parameters for the four groupings that we contend are bona fide clusters in their own right in Table 3 from all of the above analysis. We estimate errors for \( \sigma_v \) following Danese, de Zotti & di Tullio (1980). For the clusters that we name A1386-A and -B, we restrict our computation of \( \overline{cz} \) and \( \sigma_v \) to the area of overlapping circles suggested by Fig. 7 (i.e. coarsely splitting the 21 000–27 000 km s\(^{-1}\) redshift slice at RA = 177 and Dec. < −1.9) and apply the clipping technique of Zabludoff, Huchra & Geller (1990). For A1386-C and -D, we use all available redshifts in the appropriate redshift slice (Fig. 5) over the full field of view (unlike for A1386-A and -B) and apply the same redshift clipping technique. We also note that the clusters in Table 3 extend beyond an Abell radius from the original Abell (1958) definition of A1386 – this is apparent in the case of A1386-A where A1373 is the closest companion in projection.

Since our main, long-term aim in assembling these observations was to look more closely at peculiar velocities of BCMs (cf. Coziol et al. 2009; Pimbblet 2008; Pimbblet et al. 2006), we also compute the peculiar velocity, \( v_{pec} = (v_{CG} - v_{clipped})/1 + cz \), for each group in Table 3. Following Coziol et al. (2009), we express these results as a fraction of the velocity dispersion, i.e. \( v_{pec}/\sigma_v \), to determine their level of significance (Table 3).

Two of the clusters in Table 3 have BCM peculiar velocities that are small fractions of the cluster velocity dispersions: A1386-C is \( -0.15\sigma_v \) away from \( \overline{cz} \) and A1386-D is \( 0.15\sigma_v \).

Meanwhile, A1386-B is \( -0.88\sigma_v \) away from \( \overline{cz} \) and A1386-A’s BCM is \( -0.43\sigma_v \) away from \( \overline{cz} \). These values are large fractions of the velocity dispersion (see section 3.2 of Coziol et al. 2009 for a full discussion of this parameter) and may be interesting groups for further observation. These peculiar velocity results are also in contrast to the values obtained by Coziol et al. (2009). This is largely due to the careful investigation of the A1386’s substructure that we have undertaken in this work and suggests that future investigation of BCG peculiar velocities, especially in complex areas as this one, must be undertaken with equal care in order to avoid erroneous outcomes.

As a final validation of these four groupings (Table 3), we construct colour–magnitude diagrams for them and check whether we can see a defined colour–magnitude relation (e.g. Visvanathan & Sandage 1977; Bower, Lucey & Ellis 1992). This is achieved by extracting SDSS (g − r) colours around the BCM of each group (Table 3) to a radius of 0.5 within 3\( \sigma_v \) of the mean velocity given in Table 3 and comparing the location of any obvious early-type ridge line with the empirical predictions of López-Cruz, Barkhouse & Yee (2004; in particular see the equations contained in figs 3 and 4 of that work), who surveyed clusters over a comparable redshift range to the present work. One immediate issue in performing this analysis is that the equations presented by López-Cruz et al. (2004) are in the Kron–Cousins system (calibrated to Landolt 1992 standards), rather than SDSS ugriz photometry. Hence, we transform the SDSS photometry to Kron–Cousins using the transformations derived by Lupton.\(^1\) Although Lupton derived these transformations for stellar objects, these transforms should hold for galaxies that do not have significant emission lines – just as one would expect for galaxies around the colour–magnitude relation.

The resultant colour–magnitude diagrams are shown in Fig. 8 along with the López-Cruz et al. (2004) prediction for the early-type ridge line. All of the four groupings show galaxies that are consistent with the predictions of where the ridge line should lie (especially given the errors inherent in the photometric conversion to Kron–Cousins and the errors of the line given by López-Cruz et al. 2004; especially the scatter observed in fig. 4 of López-Cruz et al. 2004). Therefore, we conclude that the field of A1386 is made up of at least four subunits along the line of sight, and possibly a few filaments as well, at the high-redshift end of the distribution seen in Fig. 3. We emphasize our observations and analysis of A1386 is wider than an Abell radius at these redshifts, and therefore encompasses an area that Abell (1958) may not have examined in great detail. In passing, we note that A1386-B seems to have a modest blue fraction of galaxies (e.g. Butcher & Oemler 1984) indicating that it is more highly star-forming than the other clusters we have detailed.

5 SLOAN GREAT WALL

A1386 does not reside in just any part of the sky; it is a part of the Leo A supercluster (Einasto et al. 1997) and hence is a part of the SGW (Gott et al. 2005; Nichol et al. 2006; Deng et al. 2007; Einasto et al. 2010). Although the SGW ‘may be the largest coherent structure yet observed’ (Tegmark et al. 2004) in the Universe, it could have still plausibly been formed from random phase Gaussian fluctuations (see Tegmark et al. 2004; Gott et al. 2005) and even larger structures may yet be found (Shandarin 2009).

In Fig. 9 we demonstrate how our new radial velocities fit in with the SDSS measured velocities in the region of the SGW. Our new measurements are probing the central regions of the SGW, at RA \( \sim 11.8 \) h. This region of the SGW is where it has split into two defined filaments that stretch from \( \sim 11.3 \) to \( \sim 12.7 \) h (cf. fig. 9 of Gott et al. 2005).

\(^1\) http://www.sdss.org/dr4/algorithms/sdssUBVRITransform.html
Figure 8. Colour–magnitude diagrams for the groups identified in Table 3. The early-type ridge line is the empirical relation found by López-Cruz et al. (2004). Each group has galaxies that are consistent with this relation, therefore adding weight to the finding that these groups are real.

Figure 9. Our new observations of A1386 combined with all available literature redshifts (black dots) plotted in the context of the SGW (SDSS data shown as grey dots in the declination range of $1.5 < \delta < -3.5$). The dashed lines denote the spatial extent of our AAOmega observations. A1386 sits near the heart of the Great Wall in right ascension terms.

The first point to make is that our new observations probe both the median $cz$ range of the SGW and beyond. At A1386’s declination, we qualitatively appear to be establishing a previously hinted line-of-sight filament (Fig. 9). This can readily be seen by contrasting the redshift histogram (Fig. 3) with the points delineated by the dashed lines in Fig. 9 which denote the right ascension extent of our observations.

Our observations also better define the split in the SWG with higher fidelity than previous works. Indeed, A1386-A resides at almost the western end of this split, with A1386-B residing beyond...
the two main filaments of the SGW. Given the difference in $cz$ between A1386-B (Table 3) and the bulk of the Great Wall, we suggest that the interpretation is that this component A1386-B is likely to be infalling along the line of sight to the ‘bulk’ of the Great Wall at $cz \sim 24000$ km s$^{-1}$.

This raises the question as to whether any or all of the four groups that we have identified (Table 3) are interacting with each other. The difference in recession velocity between the groups is $\Delta_{A1386-B} = 2359$ km s$^{-1}$; $\Delta_{A1386-C} = 2267$ km s$^{-1}$; $\Delta_{A1386-D} = 2637$ km s$^{-1}$. Given the small velocity dispersion of both A1386-A and A1386-B, it is unlikely that these two groups are interacting. $\Delta_{B-SG}$ is more than 5 times the velocity dispersion of A1386-C ($\sigma_c = 451$ km s$^{-1}$), thus A1386-C is also unlikely to be interacting with A1386-B. Even $\Delta_{C-D}$ is at least $3.5 \sigma_c$ of A1386-D. Hence, we believe that these groups and clusters are probably not interacting with each other, although they may be moving coherently towards the bulk of the Great Wall. However, the analysis above does not preclude the possibility that the groups found in the present work are connected by filaments extending in a radial direction (cf. Lu et al. 2010) which could be verified with a deeper and more complete spectroscopic sample. Indeed, Fig. 9 displays hints that all of our groups may be in proximity to larger filaments (cf. Pimbblet et al. 2004).

6 SUMMARY

This work has presented a catalogue of 300 radial velocities (78 of them new) in the direction of A1386 as part of our ongoing endeavours to identify peculiar velocities of BCMs in Abell clusters. Here, we have taken a critical examination of A1386 to unravel its complex architecture and its place in the large-scale structure around it by looking at its relationship with the SGW.

We have demonstrated that A1386 is not a simple, relaxed galaxy cluster. It is composed of at least four separate clusters, perhaps more, along the line of sight that are spatially close to one another on the sky. We have delineated these structures through a combination of statistical substructure tests, presence of a dominant BCM and colour–magnitude relations. The global parameters for these new clusters are given in Table 3. Of these, A1386-A and A1386-B both have a BCM with a peculiar velocity that is a large fraction of their velocity dispersions. Our results are in contrast to the results of Coziol et al. (2009), who report different subclusters, and therefore different peculiar velocities. The only common subcluster between our two works is A1386A (as per Coziol et al. 2009), which in our work has been divided in to A1386-C and A1386-D (Table 3).

There are several walls or filaments of galaxies that pass through the line of sight to A1386. These are seen in Fig. 3 as peaks at $cz > 33000$ km s$^{-1}$. A1386 is also located near the heart of the SGW. Of the subclusters identified, we suggest that only A1386-A is associated with the SGW itself. Although the other newly identified clusters may be moving towards other mass concentrations (both in and beyond the SGW), we suggest that at this time the other clusters are not physically bound to the SGW and none of them is interacting with one another significantly.

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Table A1. The redshift catalogue. The $R$ magnitude is sourced directly from the APM catalogue. Where applicable, we have listed our targets that also appear in other catalogues (right-hand columns). The sources for these are codified as follows: (a) 2dFGRS (Colless et al. 2003); (b) 6dFGS (Jones et al. 2009); (c) HIPASS (Doyle et al. 2005); (d) Quintana & Ramírez (1995); (e) LCRS (Shectman et al. 1996); (f) UZC (Falco et al. 1999); (g) SDSS-DR7 (Abazajian et al. 2009); (h) Slinglend et al. (1998); (i) Grogin et al. (1998); (j) da Costa et al. (1998). The full table is available through the online version of this article (see Supporting Information).

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Miller C. J. et al., 2005, AJ, 130, 968

APPENDIX A: REDSZIF CATALOGUE

In Table A1, we present the new radial velocities we measured from our AAOmega observations. The designation ‘PRA’ that appears in the table refers to three of the authors of this work (KAP, IGR and HA) who created the original telescope time application, the target list and reduced the data set.

SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article.

Table A1. The redshift catalogue.

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