Photometric selection of emission-line galaxies, clustering analysis and a search for the integrated Sachs–Wolfe effect

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Accepted 2009 December 14. Received 2009 November 27; in original form 2009 February 6

ABSTRACT
We investigate the use of simple colour cuts applied to the Sloan Digital Sky Survey (SDSS) optical imaging to perform photometric selections of emission-line galaxies (ELGs) out to $z < 1$. Our selection is aimed at discerning three separate redshift ranges: $0.2 \leq z \leq 0.4$, $0.4 < z \leq 0.6$ and $0.6 < z \leq 1.0$, which we calibrate using data taken by the COMBO-17 survey in a single field (S11). We thus perform colour cuts using the SDSS $g$, $r$ and $i$ bands and obtain mean photometric redshifts of $\bar{z}_{\text{low}} = 0.32 \pm 0.08$, $\bar{z}_{\text{mid}} = 0.44 \pm 0.12$ and $\bar{z}_{\text{hi}} = 0.65 \pm 0.21$. We further calibrate our high-redshift selection using spectroscopic observations with the AAOmega spectrograph on the 4-m Anglo-Australian Telescope, observing $\approx 50–200$ galaxy candidates in four separate fields. With just 1 h of integration time and seeing of $\approx 1.6$ arcsec, we successfully determined redshifts for $\approx 65$ per cent of the targeted candidates. We compare our spectroscopic redshifts to the photometric redshifts from the COMBO-17 survey and find reasonable agreement between the two. We calculate the angular correlation functions of these samples and find correlation lengths of $\xi_0 = 0.20 \pm 0.03$, $\xi_0 = 0.17 \pm 0.03$ and $\xi_0 = 0.13 h^{-1}$ Mpc for the low-, mid- and high-redshift samples, respectively. Comparing these results with predicted dark matter clustering, we estimate the bias parameter for each sample to be $b = 0.72 \pm 0.02$, $b = 0.93 \pm 0.03$ and $b = 1.43 \pm 0.03$. We calculate the two-point redshift-space autocorrelation function at $z \approx 0.6$ and find a clustering amplitude of $s_0 = 6.4 \pm 0.8 h^{-1}$ Mpc. Finally, we use our photometric sample to search for the integrated Sachs–Wolfe signal in the Wilkinson Microwave Anisotropy Probe (WMAP) 5-yr data. We cross-correlate our three redshift samples with the WMAP $W$, $V$, $Q$ and $K$ bands and find an overall trend for a positive signal similar to that expected from models. However, the signal in each is relatively weak, with the results in the WMAP $W$ band being $w_{\text{Tg}}(<100 \text{arcmin}) = 0.25 \pm 0.27$, $0.17 \pm 0.20$ and $0.17 \pm 0.16 \mu$K for the low-, mid- and high-redshift samples, respectively. Combining all three galaxy samples, we find a signal of $w_{\text{Tg}}(<100 \text{arcmin}) = 0.20 \pm 0.12 \mu$K in the WMAP $W$ band, a significance of $1.7\sigma$. However, in testing for systematics where the WMAP data are rotated with respect to the ELG sample, we found similar results at several different rotation angles, implying the apparent signal may be produced by systematic effects.

Key words: galaxies: general – galaxies: photometry – galaxies: spiral – cosmic microwave background – large-scale structure of Universe.

1 INTRODUCTION
Imaging surveys are currently in the process of mapping out a vast region of the Universe over a large range of the electromagnetic spectrum. The pacesetter in recent years is the Sloan Digital Sky Survey (SDSS; York et al. 2000), which now provides [as of data release 6 (DR6); Adelman-McCarthy et al. 2008] photometric data for approximately 230 million distinct sources over an area of $8240 \text{deg}^2$. Current and future wide- and deep-field surveys such as SWIRE (Irwin & Lewis 2001; McMahon et al. 2001; Rowan-Robinson et al. 2008), UKIDSS (Lawrence et al. 2007), CFHTLS (Cabanac et al. 2007)
A simple route to photometric selection of different redshift samples is using the 4000 Å break feature, which passes through the optical wavelength bands from redshifts of $z = 0$ out to $z = 1$. Such selections have been used in a range of key cosmological applications, and perhaps most significant amongst these is the detection of the baryon acoustic oscillation (BAO) signature in analyses of large-scale structure. This was measured by Eisenstein et al. (2005) using spectroscopic redshifts of $>40000$ LRGs selected from the SDSS using photometric constraints based on the progression of the 4000-Å break. The measurement of the BAO signal should also be possible using suitably accurate photometric redshifts as the BAO galaxy clustering features are on scales of the order of $100 h^{-1}$Mpc (Eisenstein et al. 2001; Cole et al. 2005; Eisenstein et al. 2005).

One significant use of photometrically selected galaxies is the study of the integrated Sachs–Wolfe (ISW) effect, in which cosmic microwave background (CMB) photons are subjected to shifts in energy as they pass through the gravitational potential wells of galaxies and clusters in an accelerating Universe (Sachs & Wolfe 1967). This has been studied by a number of authors using the WMAP public DRs in combination with photometrically selected galaxy populations. Aside from the use of simple magnitude-limited galaxy samples (e.g. Fosalba, Gaztañaga & Castander 2003; Fosalba & Gaztañaga 2004; Rassat et al. 2007), this work is again dominated by the use of LRGs. For example, Padmanabhan et al. (2005b) use photometrically selected LRGs from the SDSS (covering a redshift range of $0.2 < z < 0.6$) to make a 2.5σ detection of the ISW effect in WMAP first-year data, whilst Cabré et al. (2006) combine a $z \approx 0.5$ SDSS LRG sample with the WMAP third-year data to claim a detected ISW signal of 3σ. More recently Giannantonio et al. (2008) performed a combined analysis using a number of galaxy and QSO catalogues, incorporating Two Micron All Sky Survey data (Jarrett et al. 2000), SDSS DR6 galaxies, SDSS MegaZ LRGs (Collister et al. 2007), NRAO VLA Sky Survey radio data (Condon et al. 1998), HEAO X-ray data (Boldt 1987) and the SDSS DR6 QSO catalogue (Richards et al. 2009). By combining the results from these data sets, Giannantonio et al. (2008) report a 4.5σ detection of the ISW effect and go on to use this to test a number of cosmological models. In particular, their ISW result places constraints on the mass density of $\Omega_m = 0.26^{+0.09}_{-0.07}$, assuming a flat $\Lambda$ cold dark matter ($\Lambda$CDM) cosmology.

As an alternative to the recent dominance of LRGs for large redshift surveys, we now look at the photometric selection and clustering of emission-line galaxies (ELGs). The key advantage of using ELGs in this application is the ability to identify galaxies through spectroscopic observations with relatively short exposure times, due to the emission lines with which they are most easily identified. Blake et al. (2009) have successfully used this to their advantage to undertake the WiggleZ spectroscopic survey of ELGs with the aim of measuring the BAO signal at $z \approx 0.7$. They select ELGs in the redshift range $0.5 < z < 1$ using a combination of GALEX far- and near-ultraviolet imaging with $g$, $r$ and $i$-band optical imaging from SDSS and the second Red Cluster Sequence project (Yee et al. 2007). In this case, the GALEX data allow them to select $z > 0.5$ galaxies using the Lyman-break technique, whilst the SDSS optical data allows them to limit their sample to just blue emission-line objects. They then perform spectroscopic observations using the AAOmega instrument at the 4-m Anglo-Australian Telescope (AAT), with exposure times of $<1$ h required for successful identification.

In this paper, we attempt to refine a number of photometric selections of ELGs in different redshift ranges, using optical data from the SDSS. In making greater use of the ELG population in studies of large-scale structure, we may maximize the use of the available data from such large-scale surveys as the SDSS and the upcoming VST ATLAS and Pan-STARRS surveys. We use COMBO-17 photometric redshift data in combination with SDSS data to perform a calibration of our photometric selections (Section 2). We go on to outline and review our observation programme at the AAT, which was aimed at providing a spectroscopic catalogue with which to further calibrate the photometric selections. In Section 3, we then evaluate the clustering properties of the galaxy populations contained in our photometric selections using SDSS data. We then use the full samples of $>600000$ galaxies selected from the SDSS to perform a search for the ISW effect in WMAP 5-yr data (Section 4).

We present our summary and conclusions in Section 5. Throughout this paper, we assume a $\Lambda$CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 100 h$ km s$^{-1}$ Mpc$^{-1}$.

## 2 PHOTOMETRIC SELECTION

### 2.1 Data and selection

Using SDSS imaging data, our aim is to develop a set of photometric selection criteria using the SDSS filter bands (Fukugita et al. 1996) alone to isolate ELGs in three separate redshift ranges of approximately $z < 0.4$, $0.4 < z < 0.6$ and $z > 0.6$. At these redshifts, the 4000 Å break is a key feature in the observed optical spectra of both red and blue galaxies as it moves through the $g$ and $r$ SDSS filters with increasing redshift. In ELGs however, the break is somewhat weaker than in the spectra of LRGs, whilst the continuum at wavelengths greater than 4000 Å remains lower compared with the LRG spectrum due to the dominance of young blue stars in the ELGs. These contrasts in the spectra of LRGs and ELGs inherently allow us to separate the two in colour space, whilst simultaneously facilitating photometric selections of galaxies at different redshifts.

With this in mind, we have used the Bruzual & Charlot stellar population synthesis code (Bruzual & Charlot 2003) to model the evolution of a typical ELG in the gri (AB) colour plane. We used a Salpeter IMF with a galaxy formed at $z_f = 7.9$ (i.e. with an age of 12.8 Gyr at $z = 0$) and a $\tau = 9$ Gyr exponential star formation rate (SFR). The resultant gri colour evolution track from $z = 1.0$ to $z = 0$ is shown in Fig. 1 (dashed black line). Here, we see a clear evolution in the gri colour space around which we may build a selection regime for identifying candidates in our desired redshift ranges. We also plot a track (dot–dashed line) for an elliptical galaxy
using a $\tau = 1$ Gyr exponential SFR and a redshift of formation of $z_f = 7.9$ (with solar metallicity and Salpeter IMF).

We calibrate our selections using the photometric redshift data published by the COMBO-17 team (Wolf et al. 2003; Simon et al. 2009). The data we use are from the COMBO-17 S11 field, which covers an area of 0.5 $\times$ 0.5 centred at 11h42m58s, −01d42′50″ (J2000) and the entirety of which is covered by SDSS imaging. These data provide accurate $\Delta(z/(1 + z) = 0.02)$ photometric redshifts for a total of 7248 galaxies based on broad- and narrow-band imaging using 17 different optical and near-infrared filters. We match the positions of COMBO-17 galaxies to the equivalent SDSS positions with the COMBO-17 photometric redshifts. The S11 objects are shown in the (SDSS) $g−r$, $r−i$ colour plane in Fig. 1. For the purposes of clarity, we only plot those galaxies classified as blue spirals by the COMBO-17 team in this figure; however, the location of red-sequence galaxies is indicated by the LRG evolution track (dot-dashed line). The COMBO-17 galaxies have been split into three populations for the purposes of this plot based on their assigned photometric redshift from COMBO-17: 0.2 $< z < 0.4$ (blue diamonds), 0.4 $< z < 0.6$ (green triangles) and 0.6 $< z < 1.0$ (red squares).

Based on the distribution of the photometric redshifts and the ELG evolution track presented in the above plot, there is a clear progression in the $gri$ colour plane based on ELG redshift. Further to this, areas of the plot can be isolated that should minimize the number of red-sequence galaxies, whilst maximizing the numbers of either $z < 0.4$ or $z > 0.6$ ELGs. The medium redshift range does however present significant problems. The ELG evolution track appears to pass through a region populated by both lower and higher redshift ELGs as well as low-redshift red-sequence galaxies in the 0.4 $< z < 0.6$ range.

From the above observations we construct three sets of colour cuts to preferentially select three redshift ranges. These are shown in Fig. 1 by the dotted blue box (low-redshift cut), solid green box (medium redshift cut) and dash–double-dotted red box (high-redshift cut). As discussed above, the mid-redshift range is significantly exposed to contamination from both ELGs at unwanted redshifts and red-sequence galaxies. To minimize the numbers of these, we have therefore added colour cuts to this sample based on the $r−i$, $i−z$ and $u−g$ colours of the selected galaxies. These additional cuts have also been calibrated using the COMBO-17 photometric redshifts. The details of our three selections, including the additional mid-redshift colour cuts, are given explicitly in Table 1. These cuts have been tailored to produce sky densities of candidates of $\approx100$ deg$^{-2}$ for each of the three redshift ranges in order to provide candidate numbers suitable for wide-field spectroscopic surveys performed with instruments such as the 2dF/AAOmega spectrograph.

The photometric redshift distribution for our three samples is shown in Fig. 2. This plot includes all the selected galaxies from the S11 field, including those identified as being part of the red sequence (these making up $\approx4$ per cent of the total selected across all three selections). The three selections are characterized by mean redshifts of $\bar{z}_{\text{low}} = 0.29$, $\bar{z}_{\text{mid}} = 0.44$ and $\bar{z}_{\text{hi}} = 0.65$, with standard deviations of $\sigma_{\text{low}} = 0.05$, $\sigma_{\text{mid}} = 0.08$ and $\sigma_{\text{hi}} = 0.21$.

For the purposes of this paper, we now use our three selections to create three data sets from the SDSS galaxy catalogue. We apply the selections to the SDSS DR6 taking our data from the PhotObjAll table available on the SDSS Catalog Archive Server (CASSJOBS) at http://casjobs.sdss.org. Aside from the colour–magnitude criteria given in Table 1, we reject objects which do not meet the following criteria:

(i) TYPE=3 (i.e. classified as a galaxy);
(ii) NCHILD=0;
(iii) Flagged as BINNED1, BINNED2 and BINNED3; (iv) $90^\circ < RA < 270^\circ$.

| Low redshift | Mid-redshift | High redshift |
|--------------|--------------|---------------|
| $19.0 < i < 20.0$ | $19.0 < i < 20.2$ | $19.5 < i < 20.5$ |
| $r−i > 0.3$ | $g−r > 1.2(r−i) + 0.9$ | $r−i > 0.5$ |
| $g−r < 1.2(r−i) + 0.9$ | $g−r < 1.2(r−i) + 0.9$ | $g−r < 1.2(r−i) + 0.06$ |
| $g−r > −1.2(r−i) + 0.75$ | $g−r > −1.2(r−i) + 1.65$ | $g−r > 1.2(r−i) − 0.6$ |
| $g−r < −1.2(r−i) + 1.3$ | $r−i > −(i−z) + 0.5$ | $g−r < −1.2(r−i) + 2.2$ |
| $−2.0 < u−g < 1.0$ | $−2.0 < u−g < 1.0$ | $−2.0 < u−g < 1.0$ |
| $i−z > 0.55$ | $i−z > 0.55$ | $i−z > 0.55$ |

Note: These are illustrated in the $ugr$ colour plane in Fig. 1.
2.2 Observations

An important element of this work is the calibration of the photometric selection samples with spectroscopic observations to confirm the achievable redshift distribution of our selections. To this end, we have performed spectroscopic observations of our \( z \approx 0.7 \) sample using the AAOmega spectrograph at the AAT (Saunders et al. 2004; Sharp et al. 2006). AAOmega is a double beam spectrograph fed by 2.1 arcsec diameter fibres, which allows the simultaneous observation of up to \( \approx 360 \) objects in a circular field of view of diameter 2\'.

Observations were taken on the AAOmega instrument at the Anglo-Australian Observatory (AAO) on the nights of 2006 March 4 and 6. The spectrograph was configured using the 5700 Å dichroic, with the 580V grating mounted in the blue-arm and the 385R grating in the red arm. The 580V grating gives a wavelength coverage of 370 to 580 nm, with a pixel size of 0.1 nm pixel\(^{-1}\) and the 385R a coverage of 560 to 880 nm, with a pixel size of 0.16 nm pixel\(^{-1}\). Both provide a resolution of 1300. In total, AAOmega offers 400 fibres per observation; however, a significant number of these were at times used for other projects (e.g. Ross et al. 2008) and were locked to guide stars, sky targets or simply malfunctioning, and so our target numbers range from \( \sim 50 \) to 230 per observation. We targeted four 2dF with multiple exposures of 1200 s each. The observations are summarized in Table 2. The four observed fields are targeted towards the Cosmic Evolution Survey (COMOS; Scoville et al. 2007) field, the d05 and e04 fields from the 2dF-SDSS LRG and QSO (Croom et al. 2004) survey and the S11 field from COMBO-17.

Target objects were selected using our selection criteria applied to the SDSS data available for each of the fields. Over the course of five nights, seeing ranged from \( \sim 1.5 \) to 3.0 arcsec, with a mean of \( \sim 2.0 \) arcsec. All observations were flat fielded, arc calibrated and combined using the AAO’s 2dFDR tool. Approximately 20 per cent of fibres were affected by an early instrumentation problem known as fringing, which led to an almost sinusoidal signal in the output. In the S11 field, this affected 27 of the fibres targeted on ELG candidates. A further problem is encountered due to the strong sky emission lines above 8250 Å. These limit the identification of \( \mathrm{H}\beta \) and \( \mathrm{[O\,\text{n}] in \sim 0.65 \) to 0.7; however, they do not interrupt identification of \( \mathrm{[O\,\text{n}] and so the impact of the sky lines is limited.

2.3 Galaxy redshifts

We use the 2dF Galaxy Redshift Survey (2dFGRS) software autoz (Croom et al. 2001) and runz (Colless et al. 2001) to search for emission features with which to identify galaxies in our observed sample and determine redshifts. autoz performs an initial identification of each spectrum, fitting absorption and emission features. Each fibre spectrum was then evaluated by eye to assign a redshift and quality rating, \( q_{\text{op}} \) (which ranges from 0 to 5 depending on the confidence of the identification). Only objects with \( q_{\text{op}} \geq 3 \) were accepted as positive identifications.

Examples of the spectra obtained with the AAOmega instrument are provided in Fig. 3. The spectra are all binned to a bin width of \( \approx 10 \) Å, and key emission and absorption features are marked. We also show the unbinned data for the \( \mathrm{[O\,\text{n}] feature (insets), where it is evident that the doublet nature of the feature is marginally detectable at the observed resolution. Although data were obtained on both the blue and red arms, only spectra from the red arm are plotted here as there are few features useful for identification in the blue wavelength range given the signal-to-noise ratio of our data. The key emission features that facilitate the identification of these galaxies with short exposure times, i.e. \( \mathrm{[O\,\text{n]}, \mathrm{H}\beta \) and the \( \mathrm{[O\,\text{m}] doublet, are all evident in these spectra.

Table 2. Coordinates of the four fields targeted with the number of \( gr \) selected ELG candidates in each 2dF.

| Field | COSMOS | d05 | e04 | S11 |
|-------|--------|-----|-----|-----|
| Date  | 06/03/06 | 04/03/06 | 04/03/06 | 06/03/06 |
| RA    | 150:118 | 200:399 | 221:899 | 175:741 |
| Declination | +2:2052 | -0:2124 | -0:2141 | -1:7159 |
| Exposure time | 3 × 1200 s | 3 × 1200 s | 4 × 1200 s | 3 × 1200 s |
| Seeing | \( \approx 3.0 \) arcsec | \( \approx 2.0 \) arcsec | \( \approx 2.5 \) arcsec | \( \approx 1.6 \) arcsec |
| Candidates | 378 | 329 | 343 | 391 |
| Targeted | 217 | 45 | 225 | 219 |
| ELG redshifts | 44 | 10 | 84 | 142 |
There were no positive identifications of galaxies with just absorption-line features and no emission lines in the spectroscopic observations. It is likely however that any absorption-line galaxies targeted remained unidentified given the relatively short exposure times, which make it difficult to confidently identify absorption-line features in the spectra.

A summary of the numbers of ELGs identified in our four fields is provided in Table 2. Our most successful field was the COMBO-17 S11 field in which we were able to target 219 ELG candidates in seeing conditions of ≈1.6 arcsec. In this field we identified 121 of the 219 candidates as being ELGs from their emission lines with a confidence of $q_{op} \geq 3$. In total, we were able to identify 311 ELGs over a combined area of 12.4 deg$^2$, giving an average sky density of 25 deg$^{-2}$. However, three of the observed fields suffered poor seeing conditions of $\geq 2.0$ arcsec, limiting our ability to successfully identify objects in these fields. At worst, completeness was reduced to $<25$ per cent in the COSMOS field due to the seeing of $\approx 3.0$ arcsec. However, in the more reasonable observing conditions encountered with the observations in the S11 field (where the seeing was 1.6 arcsec), we find that the identification rate is a more promising ~65 per cent, with a sky density of $\approx 40$ deg$^{-2}$.

Fig. 4 gives the redshift distribution of the spectroscopically confirmed galaxies in the S11 field. The plot incorporates all galaxies identified in the S11 field and the original photometric redshift distribution from COMBO-17 data (black dashed line) also from the S11 field. Our spectroscopic sample follows the expected distribution...
closely, with $z_{\text{spec}} = 0.66 \pm 0.23$ (compared to $z_{\text{phot}} = 0.65 \pm 0.21$). There is some contamination from lower redshift (i.e. $z < 0.5$) galaxies, and in the spectroscopic sample this is at a level of $\approx 18$ per cent (compared to a level of $\approx 23$ per cent obtained with the COMBO-17 photometric redshift sample).

Fig. 5 shows identifications as a function of source magnitude in the S11 field. The lower panel shows number counts of spectroscopically confirmed galaxies exhibiting emission lines ($N_{\text{em}}$, dark bars) and of all objects targeted with AAOmega fibres ($N_{\text{T}}$, pale bars), whilst the upper panel shows the fraction $N_{\text{em}}/N_{\text{T}}$. The consistency of the 65 per cent identification rate across our magnitude range is evident and we are clearly reaching the $i = 20.5$ mag limit successfully. A small falloff in the fraction of ELGs identified is observed in the fainter magnitude bins; however, numbers still remain high.

In Fig. 6, we compare our spectroscopically determined redshifts against the COMBO-17 photometric redshifts for those galaxies lying in the central $0.5 \times 0.5$ region covered by the COMBO-17 data. The vertical error bars represent the $\sigma_{\Delta z} \approx 0.03$ error quoted by the COMBO-17 team for their photometric redshifts. We find a total of 24 objects that have both COMBO-17 photometric redshifts and spectroscopic redshifts from this work. Overall there appears to be good agreement between the data with just four outliers (taken here as a difference between the photometric and spectroscopic results of $3 \sigma_{\Delta z}$) having significantly different redshifts. The spectra for all four of these objects are given in Fig. 3 and each of the outliers are marked in Fig. 6 by the spectrum number (1, 3, 5 and 6) from Fig. 3. We find a mean offset between the spectroscopic and photometric redshifts of $\Delta z = 0.01 \pm 0.04$ (after excluding points 1 and 5).

We show in Fig. 7 the distribution of spectroscopically confirmed $z > 0.5$ ELGs (filled blue circles), $z < 0.5$ ELGs (green triangles) and unidentified objects (red crosses) in the $g - r$ versus $r - i$ colour plane. It is evident that the $z > 0.5$ ELGs are reasonably evenly spread in the $g - r$ versus $r - i$ colour plane as are the objects without any discernible emission, although there is some bias in these to be towards the redder end of the selection in both $r - i$ and $g - r$. The $z < 0.5$ ELGs appear to be biased towards the upper left limits of the selection region, towards the low-redshift main sequence. These may be further reduced by altering our constraints; however, this would also remove a significant number of the galaxies at the same time. The model evolution track from Fig. 1 is again plotted for reference.

Now looking at the properties of the galaxy spectra, we measure the equivalent widths of the nebular emission lines by fitting Gaussian curves to the $[\text{O} \text{II}]$ 3727 Å, $\text{H} \beta$ and $[\text{O} \text{II}]$ 5007 Å lines. We were able to measure equivalent widths with confidence for $[\text{O} \text{II}]$ 3727 Å, $\text{H} \beta$ and $[\text{O} \text{II}]$ 5007 Å in 109, 53 and 51 of the galaxies.
Figure 7. Spectroscopic results from the S11 and e04 fields. We show objects identified as \( z \geq 0.5 \) ELGs (filled blue circles), \( z \leq 0.5 \) ELGs (green triangles) and objects with no identified redshift (red crosses). The same evolution track as plotted in Fig. 1 is also shown.

Figure 8. ‘Blue diagnostic’ diagram based on Lamareille et al. (2004). Line ratios are plotted for the subsample of our spectroscopically observed sample for which we have equivalent widths for the \([\text{O} \, \text{II}]\) \( \lambda 3727 \), \( H\beta \) and \([\text{O} \, \text{III}]\) \( \lambda 5007 \) nebular emission lines. The solid line marks the limit estimated by Lamareille et al. (2004) between star-forming galaxies and AGN and the dashed lines show the region of uncertainty. In total, 22 objects lie within the star-forming region of the diagnostic plot and are marked by filled blue circles. A further five lie within the overlap region (cyan stars) and none of the objects lies within the AGN region.

in our sample, respectively. From these, we determined mean equivalent widths of 23.0, 8.12 and 8.98 Å for \([\text{O} \, \text{II}]\) \( \lambda 3727 \), \( H\beta \) and \([\text{O} \, \text{III}]\) \( \lambda 5007 \), respectively. These mean equivalent widths are broadly consistent with other measurements of emission lines in late-type galaxies (e.g. Kennicutt 1992; Shi, Gu & Peng 2006). In 27 of these galaxies, we were able to measure all three of the above nebular emission lines with confidence and have attempted to evaluate the presence of active galactic nuclei (AGN) in our sample using the ‘blue diagnostic’ constraints of Lamareille et al. (2004), which are based on the \([\text{O} \, \text{II}]\) \( \lambda 3727/H\beta \) and \([\text{O} \, \text{III}]\) \( \lambda 5007/H\beta \) line ratios. This is shown in Fig. 8, where the solid line marks the estimated division between AGN (above) and star-forming galaxies (below). The dashed lines mark the region of uncertainty between the two populations. In all, 22 of this subsample fall within the star-forming galaxy region, whilst the remaining five (two of which have large uncertainties) fall within the uncertain region and none lie in the AGN region. Within the reliability of the blue diagnostic diagram, we can say that our sample is dominated by star-forming galaxies and this method shows no positive evidence for AGN contamination of our sample although there are a small number of borderline cases.

Fig. 9 shows a composite spectrum of all of the confirmed ELGs over all redshifts, with significant emission and absorption features labelled. The key emission lines used in our spectral identification (i.e. \([\text{O} \, \text{II}], H\beta \) and \([\text{O} \, \text{III}]\)) are clearly evident. We also see the Balmer absorption features redwards of the \([\text{O} \, \text{II}]\) emission, whilst the weak ELG 4000-Å break is also apparent in this composite.

3 CLUSTERING

3.1 Angular correlation function

We now evaluate the angular correlation function for a sample of galaxies selected based on our three photometric selections. The data sets taken from SDSS DR6, as described in the previous section, are used for this purpose. We calculate the angular correlation function of the samples using the Landy–Szalay estimator:

\[
w(\theta) = \frac{(DD)}{(RR)} - 2 \frac{(DR)}{(RR)} + 1,
\]

where \( DD \) and \( n_R \) are the numbers of galaxy–galaxy pairs and the total number of galaxies, respectively. For these calculations, we use a random catalogue which exactly matches the sky coverage of our SDSS galaxy samples and with a factor of 20 more random points than galaxies in each of our galaxy samples. The total number of random points is given by \( n_R \) and \( DR \) is simply the number of galaxy random pairs. Statistical errors are estimated using field-to-field errors, using 16 separate fields within our complete field. Our results for the three photometric samples are shown in Fig. 10 where the blue triangles, green squares and red crosses show the low-, mid- and high-redshift samples, respectively.

From these measurements of the angular correlation function, we now estimate the two-point correlation function \([2PCF, \xi(\theta)]\) using Limber’s formula. We make an estimate of \( \xi(\theta) \) for each of the samples using a double power law with a central break, i.e. \( \xi(<r_b) = (\frac{r}{r_b})^{-\gamma_1} \) and \( \xi(>r_b) = (\frac{r}{r_b})^{-\gamma_2} \). This is then combined with our best estimate of the redshift distribution (based on the COMBO-17 photometric redshift data for the low- and mid-redshift samples and the spectroscopic redshift data for the high-redshift sample) to calculate the resultant \( w(\theta) \) with Limber’s formula. A full treatment of this calculation is given by Phillipps et al. (1978). We then perform a \( \chi^2 \) fitting, in the range 2 arcmin \(<\theta<20\) arcmin to our data. The best-fitting models are plotted with the data in Fig. 10, whilst the associated parameters are listed in Table 3. We find reasonable fits to both the low- and mid-redshift samples, the low-redshift sample being well fitted by a double power law with a break at 0.5 \( h^{-1} \) Mpc and the mid-redshift sample by just a single power law. We note, however, that we struggle to fit to the high-redshift sample with either a double or single power law. This is largely due to strong deviations from a simple power law trend at separations of \(<2\) arcmin. This results in large \( \chi^2 \) values for our attempts to fit the correlation function in this range. The angular correlation function does however return to a simple power law
Figure 9. Composite spectrum of the 280 successfully identified ELGs. The key emission-line features used for identification are clearly visible: [O II], Hβ and [O III], whilst absorption features which are difficult to observe in individual spectra are now evident.

Figure 10. The angular correlation functions, \( w(\theta) \), for our three photometric redshift selections. Blue crosses, green diamonds and red squares represent the low- (\( z < 0.4 \)), mid- (\( 0.4 < z < 0.6 \)) and high-redshift (\( z > 0.6 \)) samples, respectively. The best-fitting power-law models are plotted through each set of data.

At separations of \( 2 \text{arcmin} < \theta < 20 \text{arcmin} \) where we are able to provide a reasonable power-law fit using the Limber method.

From our estimates of \( \xi(r) \), we now go on to estimate the bias of each sample. The biasing parameter, \( b \), quantifies the relative clustering of a given galaxy population compared to the underlying dark matter (DM) distribution (Tegmark & Peebles 1998). This can be expressed as the following:

\[
\xi_{\text{gal}}(r) = b^2 \xi_{\text{DM}}(r) \tag{2}
\]

Here, \( \xi_{\text{gal}}(r) \) is the 2PCF of the galaxy sample and \( \xi_{\text{DM}}(r) \) is the 2PCF of DM at the same epoch. We determine the DM correlation function by first using the Code for Anisotropies in the Microwave Background (\textsc{CMB}; Lewis, Challinor & Lasenby 2000) software to estimate the DM power spectrum at the mean redshifts of each of our galaxy samples. The power spectrum is calculated using the \textsc{halofit} model (Smith et al. 2003) to fit non-linear features, at each of the mean redshifts of our samples. With the DM power spectra calculated at each redshift, we then simply calculate the corresponding 2PCFs via the Fourier transform:

\[
\xi_{\text{DM}}(r) = 4\pi \int_0^\infty k^2 P(k) \frac{\sin(kr)}{kr} \, dk. \tag{3}
\]

We now estimate the bias by evaluating the DM and the galaxy 2PCFs to a maximum separation of 20 Mpc (Croom et al. 2005). This limit restricts the calculations to the linear regime at which our fits to the correlation function are still valid. Thus, the biasing parameter can be estimated using

\[
b^2 = \frac{\bar{\xi}_{\text{gal}}(20)}{\bar{\xi}_{\text{DM}}(20)}, \tag{4}
\]

where \( \bar{\xi}(x) \) is given by

\[
\bar{\xi}(x) = \int_0^x r^2 \xi(r) \, dr. \tag{5}
\]

We show \( \bar{\xi}(20) \) for each of our three redshift samples in Fig. 11 (denoted by the stars). For comparison, we also plot \( \bar{\xi}(20) \) for the 2dFGRS late-type galaxy samples of Norberg et al. (2002). These are split into absolute magnitude bins of \(-18 < M_{Bj} - 5 \log_{10}(h) < -19\), \(-19 < M_{Bj} - 5 \log_{10}(h) < -20\), \(-20 < M_{Bj} - 5 \log_{10}(h) < -21\) and \(-20.5 < M_{Bj} - 5 \log_{10}(h) < -21.5\)

Table 3. Comoving correlation lengths, \( r_0 \) and power-law slopes, \( \gamma \), for the double power-law model used to provide fits to the angular correlation functions for each redshift selection.

| \( z \)   | \( r_0(h^{-1}\text{Mpc}) \) | \( r_0(<r_0)(h^{-1}\text{Mpc}) \) | \( \gamma(<r_0) \) | \( r_0(>r_0)(h^{-1}\text{Mpc}) \) | \( \gamma(>r_0) \) | \( b \)   |
|--------|-----------------|-----------------|-----------------|-----------------|-----------------|--------|
| 0.29 ± 0.05 | 0.5             | 1.30 ± 0.03     | 2.21 ± 0.03     | 2.78 ± 0.08     | 1.55 ± 0.03     | 0.72 ± 0.02 |
| 0.44 ± 0.08 | n/a            | n/a            | n/a            | 3.71 ± 0.11     | 1.65 ± 0.03     | 0.92 ± 0.03 |
| 0.65 ± 0.21 | 0.5             | 3.40 ± 0.3      | 2.30 ± 0.05     | 5.50 ± 0.13     | 1.67 ± 0.03     | 1.43 ± 0.03 |
are based on the photometric redshift distributions from the COMBO-17 S11 field, which as yet have not been fully calibrated. We note that the low-redshift sample shows a relatively low clustering strength in Fig. 11 and a low bias compared with the mid-redshift sample, which we predict to have a relatively similar absolute luminosity range. This may be the result of an underestimate of the mean redshift of the low-z sample from the number of photometric redshifts available.

Looking at the low- and mid-redshift ranges we find that the clustering measurements suggest an increase in the clustering amplitudes of the ELGs from redshifts of $z = 0.3$–$0.5$ to more recent epochs if they are to evolve to have equivalent clustering properties to star-forming populations of comparable absolute magnitude ranges (i.e. the $-19.5 > M_b > -20.5$ 2dF sample) in the nearby Universe.

The high-redshift sample appears more consistent with a no-evolution model if it is to evolve to have similar clustering properties to the most comparable 2dF samples (i.e. $-20.5 > M_b > -21.5$) in the nearby Universe. However, the stable and long-lived clustering evolution models are still only 1–1.5σ above the brightest 2dF $\xi(20)$ value and therefore cannot be ruled out by the present accuracy of the 2dF late-type data.

3.2 Redshift-space correlation function

We now estimate the redshift-space correlation function, $\xi(s)$, using $z > 0.5$ galaxies identified with $q_{op} \geq 3$ from the four fields observed with AAOmega. The redshift distribution from Fig. 4 was used to create random catalogues with which to perform the autocorrelation analysis. In each field, we use a catalogue of $20\times$ the number of random points as galaxies in that field. In total, this calculation encompasses 276 galaxies across 12.6 deg$^2$.

We use the correlation estimator given in equation (1) to determine $\xi(s)$, whilst errors are estimated using Poisson errors. The result is shown in Fig. 12 (filled square points). We fit the $\xi(s)$ measurement with a single power law [noting that the break used in the double power laws previously lies below the range of our $\xi(s)$ result] and find a best fit (using a fixed slope of $\gamma = 1.8$) given by a clustering length of $\theta_c = 6.4 \pm 0.8$ kpc (solid line).

We also show the expected $\xi(s)$ determined from the power-law form of $\xi(r)$ given by our estimate of $w(\theta)$ (dashed line). To do this, we take the power-law form and apply both coherent infall and random pairwise velocity effects. The coherent infall imprint on the correlation function is characterized by the infall parameter, $\beta$, which is given by

$$\beta = \frac{\Omega_m(z)^{0.55}}{b},$$

where $\Omega_m(z)$ is the mass density at the required redshift and $b$ is again the sample bias (Kaiser 1987). Using the value of $b = 1.43$ from Table 3, this gives a value of the infall parameter of $\beta = 0.54$. For the random pairwise velocities, we use a value of $a = 500$ km s$^{-1}$ as a reasonable estimate of the random motions based on the 2dFGRS data (Hawkins et al. 2003). The expected $\xi(s)$ was then calculated using the relations given in Hawkins et al. (2003). Based on this calculation, we see from Fig. 12 that we find good agreement between the $\xi(s)$ of our observed spectroscopic sample and that determined from the photometric data, within the associated errors.
are less likely to reside in rich clusters and so we may expect the ISW signal to be less affected by the Sunyaev–Zel’dovich (SZ) effect produced as CMB photons pass through hot intracluster gas. This potentially provides an interesting alternative to the highly clustered LRG samples used in a number of previous studies.

4.2 Data
For this ISW analysis, we use the three galaxy samples described thus far in this paper. The redshift distributions that we use for each of the samples are given in Fig. 2 in the case of the low- and mid-redshift samples (estimated from photometric redshifts for a subset of the whole sample) and in Fig. 4 in the case of the high-redshift sample (estimated from spectroscopic redshifts for a subset of the whole sample). The number densities of each of the samples are $103\text{ deg}^{-2}$, $71.9\text{ deg}^{-2}$ and $85.1\text{ deg}^{-2}$ for the low-, mid- and high-redshift samples.

For this cross-correlation, we have used the W-, V-, Q- and K-band temperature maps from the WMAP 5-yr DR (Hinshaw et al. 2009). We use the full-resolution maps in all cases. Before performing the cross-correlation we apply two masks to the data. The first is the WMAP KP0 mask (Bennett et al. 2003) which removes the majority of the galactic (Milky Way) foreground and is the most rigorous mask provided by the WMAP team. Secondly we mask the data to match the coverage of our SDSS DR6 galaxy samples, which is described further below.

Pixelized sky-density maps are constructed from each of the three galaxy samples using the HEALPIX software. These are constructed with a resolution identical to the WMAP temperature maps characterized by the HEALPIX parameter $N_{SIDE} = 512$ (pixel width $\approx 7\text{ arcmin}$. We then limit our galaxy sample to incorporate only the contiguous north galactic pole region of the SDSS. Thus, our sample is limited to $100 < RA < 270^\circ$, and stripes 39, 42 and 43 are also excluded.

4.3 Method
Following the work of Fosalba et al. (2003) and Cabré et al. (2006), we use the cross-correlation of the galaxy and WMAP data as the expectation value of the product of the galaxy overdensity, $\delta_g$, and the normalized CMB anisotropy temperature, $\Delta T = T - T_{CMB}$, as a function of the angular separation, $\theta$. This is given by

$$w_{Tg}(\theta) = \frac{1}{n_A n_b} \sum_{i,j} \frac{\Delta_T(\theta) \delta_g(\theta_j)}{n_{A,i} n_{B,j}}.$$  (9)

Again following Fosalba et al. (2003) and Cabré et al. (2006), the form of the ISW as probed by a given galaxy population can be expressed by the following Legendre polynomial expansion:

$$w_{Tg}^{ISW}(\theta) = \sum_l \frac{2l+1}{4\pi} p_l(\cos \theta) C_{G/T}^{ISW}(l).$$  (10)

$C_{G/T}^{ISW}(l)$ is simply the ISW/galaxy population power spectrum as given by

$$C_{G/T}^{ISW}(l) = 4 \frac{4}{(2l+1)^2} \int W_{ISW}(z) W_G(z) \frac{H(z)}{c} P(k) dz,$$  (11)

where $P(k)$ is the mass power spectrum and $W_{ISW}(z)$ and $W_G(z)$ are given by

$$W_{ISW}(z) = 3 \Omega_m \left( \frac{H_0}{c} \right)^2 \frac{d[D(z)/a]}{dz}$$  (12)
Photometric selection of emission-line galaxies

Figure 13. Cross-correlation between the low-redshift galaxy sample and the WMAP V-band data. The solid line shows the predicted model. Errors are field to field based on splitting the data sample into 16 distinct segments.

Figure 14. As in Fig. 13 but with our mid-redshift sample of ELGs.

\[ W_G(z) = b(z) \phi(z) D(z), \]  

(13)

where \( D(z) \) is the linear growth rate and \( b(z) \) is the bias of the galaxy population (taken from Section 3). \( \phi(z) \) is the galaxy selection function, set from the \( n(z) \) distribution of each of the galaxy samples.

4.4 Results and error analysis

We perform the cross-correlation using the NPT (N-point spatial statistic) software (Gray et al. 2004) with the weighting for each pixel given by the galaxy density, \( \delta_g \), and the CMB anisotropy temperature, \( \Delta T \). The results are shown in Figs 13 to 15 for four WMAP bands: \( W, V, Q \) and \( K \). We also plot the predicted result using predictions based on equation (6) of Cabrè et al. (2006).

We estimate the errors on the cross-correlation analysis using field-to-field errors. For this purpose, we split the studied region into 16 approximately equal area subfields and recalculate the cross-correlation within each subfield. The error in each angular bin is thus estimated as \( \sigma / \sqrt{n} \), where \( \sigma \) is the standard deviation across the subfields and \( n \) is the number of subfields.

Overall, the results for the \( Q, V \) and \( W \) bands show reasonable agreement with the standard model predictions although the errors are large and correlated. Otherwise, we only note that for the low- and mid-redshift samples there also appears a spike at around 300 arcmin. Although this does not appear in Fig. 15 for the high-redshift sample, similar features are seen in ISW analyses of SDSS 18 < \( r < 19 \) and 19 < \( r < 20 \) mag-limited galaxy samples (see figs 12a,b of Sawangwit et al. 2009). We believe that this feature is caused by some unknown artefact in either the WMAP or SDSS data.

Summing over all bins at \( \theta < 100 \) arcmin, we find amplitudes for \( w_{Tg}(<100 \text{arcmin}) \) in the WMAP \( W \) band of 0.25 ± 0.27, 0.17 ± 0.20 and 0.17 ± 0.16 \( \mu \)K for the low-, mid- and high-redshift samples, respectively. Similar results are obtained with the \( V \) and \( Q \) bands, whilst the \( K \) band (which has a greater level of galactic contamination and a lower resolution) is less consistent, giving signals of \( w_{Tg}(<100 \text{arcmin}) = 0.13 \pm 0.36, -0.16 \pm 0.29 \) and 0.38 ± 0.18 \( \mu \)K for the low-, mid- and high-redshift samples, respectively.

We also evaluate the significance of the observed correlation by repeating the cross-correlation with rotated realizations of the WMAP data. This method uses the data itself in place of random realizations by rotating the masked WMAP data in 30° steps in galactic longitude. We note at this point that rotating in RA would lead to the galactic plane entering the field of view and although the galactic plane region is masked, it would reduce the number pixels in the analysis significantly. For consistency, we also rotate the WMAP Kp0 mask before applying it to the galaxy density map. The result of this treatment, using the high-redshift sample, is given in Fig. 16. Here, the \( w_{Tg}(<100 \text{arcmin}) \) signal is plotted as a function of rotation of the WMAP data through a full 360° in galactic longitude. The dotted line shows the non-rotated signal. Again we see that the positive signal that we see in the data does not appear statistically significant, with the rotated results showing a large amount of scatter around \( w_{Tg}(<100 \text{arcmin}) = 0 \) \( \mu \)K and two of the results (at 30° and 90°) showing more significant positive correlation than the non-rotated result.
from incorrect correction for dust extinction, contamination from
galactic foregrounds, contamination from cluster SZ signals and
contamination from point sources. Ultimately, given the combina-
tion of these systematic errors and our estimated statistical errors,
no detection of the ISW effect can be claimed at this point with this
analysis.

5 CONCLUSIONS

Colour selected samples are an extremely useful tool in modern
astronomy and cosmology. They offer a cheap route to large galaxy
redshift surveys, facilitating investigations in several key areas of
interest, including the study of dark energy via both the BAOs
and the ISW. With this in mind, we have developed photometric
selections with which to identify galaxies in three broad redshift
ranges characterized by $z = 0.29 \pm 0.05, 0.44 \pm 0.08$ and $0.65 \pm
0.21$. Applying these to SDSS data, we are able to select galaxy
samples covering the given redshift ranges down to magnitudes of
$i \approx 20.5$.

The calibration of the high-redshift sample has been performed,
using the AAOmega spectrograph at the AAT to provide spectro-
scopic redshifts for this sample. From these observations, we have
shown that it is possible to target and spectroscopically identify
$z > 0.5$ star-forming galaxies with integration times of just 1 h on
the 4-m AAT. The results of this have shown our high-redshift se-
lection to work well, giving a close match to the expected redshift
distribution, with $\bar{z} = 0.66 \pm 0.23$. Further, this has proven that
our selection can be a firm basis on which to conduct large-scale
spectroscopic surveys of $z > 0.5$ ELGs.

We have investigated the clustering properties of our three pho-
tometric samples using the angular correlation function. By fitting
the angular correlation function using Limber’s formula, we esti-
mate the real-space clustering properties of the samples and find that
both the low- and high-redshift populations are best fitted by double
power laws, whilst the mid-redshift population seems best fitted by
a single power law. From these calculations, we estimate clustering
lengths (at $r > 0.5 \text{ Mpc}$) of $2.78 \pm 0.08, 3.71 \pm 0.11$ and
$5.50 \pm 0.13 \text{ h}^{-1} \text{ Mpc}$ for the low-, mid- and high-redshift samples,
respectively. Further to this, from our spectroscopic observations
we measure a clustering length for the high-redshift sample of $6.4
\pm 0.8 \text{ h}^{-1} \text{ Mpc}$ in agreement with the measurement based on the
angular clustering measurement. Comparing these clustering mea-
urements with comparable populations of late-type galaxies from
2dF data, we note that the high-redshift sample appears to have an
unexpectedly high clustering strength.

The development of photometric redshift selections has a number
of scientific applications, not least the evaluation of the ISW effect.
We have used our photometric selection to evaluate the ISW effect
in the region of the SDSS by cross-correlating the density fluctua-
tions in our galaxy distributions with the CMB anisotropies from the
WMAP 5-yr data. The results obtained using all three data sets show
a positive correlation in accordance with the predicted model.
However, none of these three prove to be significant, with signals
in the $\text{WMAP W}$ band of $(0.25 \pm 0.27, 0.17 \pm 0.20)$ and $(0.17 \pm
0.16) \mu K$ for the low-, mid- and high-redshift samples, respec-
tively. We attempt to improve our statistics by combining the three
redshift samples, which results in a signal of $(0.20 \pm 0.12) \mu K$ when cross-
correlated with the $\text{WMAP W}$ band, still only marginal ($1.67 \sigma$).

Also in tests of contamination by systematics, we found similar
results at arbitrary angles of rotation between the CMB data and
the ELG samples which means that no detection of the ISW can be
claimed above the random and systematic noise in this analysis.
ACKNOWLEDGMENTS

We thank C. Wolf for supplying the COMBO-17 photometric redshift catalogue data and the staff of the AAO for their work in operating the AAOmega facility during our observations. Specific thanks also goes to Bob Sharp for assistance during the AAT observations. We would also like to thank Shirley Ho for comment and input to this work. This paper has used data from both the SDSS and WMAP projects. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society and the Higher Education Funding Council for England. The SDSS Web Site is http://www.sdss.org/. WMAP is the result of a partnership between Princeton University and NASA’s Goddard Space Flight Center. Scientific guidance is provided by the WMAP Science Team. RMB and NPR acknowledge the support of a STFC PhD Studentships. SMC acknowledges the support of an Australian Research Council QEII Fellowship and a J. G. Russell Award from the Australian Academy of Science.

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