Near-Infrared Imaging of a Group or Cluster of Galaxies at a Redshift of 2.39

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Abstract. At $z = 2.39$, the cluster around 53W002 is one of the most distant groups or clusters of galaxies known to date. At this redshift the 4000Å-break falls between the $J$ and $H$ bands, thus our infrared observations are designed to identify cluster members by a red $J - H$ colour. Out of the 42 objects we have detected in the field, we find ten galaxies with $J - H > 1.0$ and $K > 18.8$, redder and fainter than the radio galaxy, and consistent with the presence of a 4000Å-break at the cluster redshift. Two of these reddest galaxies have been confirmed spectroscopically. The colours, sizes and location of these infrared-selected galaxies suggest a cluster much more similar to those nearby than revealed by Hubble Space Telescope observations alone.

1. Introduction

An important recent breakthrough in the search for high-redshift galaxies has been the technique of Lyman-limit imaging, pioneered by Steidel, Pettini & Hamilton (1995). They discovered a substantial population of star-forming galaxies at $3.0 < z < 3.5$, selected using a custom set of broadband filters designed to identify the presence of the 912Å Lyman break at these redshifts. The successful confirmation of their redshifts via deep Keck spectroscopy (Steidel et al. 1996a) has led to many more applications of this technique (for example, Steidel et al. 1996b; Stevens, Lacy & Rawlings 1998). However, this selection method is strongly biased towards blue star-forming objects, and a similar bias is also present in narrow-band searches designed to identify high-redshift objects via strong emission lines (for example, Hu, McMahon & Egami 1996; Malkan, Teplitz & McLean 1996). This is unfortunate since the passively evolving stellar population of a galaxy can be masked with relative ease by even a small starburst, and it is the reddest, oldest, most-passive systems at any redshift which are of greatest importance for constraining the epoch of elliptical galaxy formation and indeed the age of the Universe.

In order to find these passively evolving galaxies one needs a selection technique that is sensitive to an old stellar population rather than a young one. Such a diagnostic is the 4000Å-break — the step in a galaxy’s spectrum due to Balmer continuum absorption, calcium H and K lines and, at a slightly larger wavelength, the iron G-band. The strength of the break is indicative of the age of the stellar population — an evolved galaxy will show a large break, whereas a young/star-forming galaxy will have a much weaker break. This should be con-
trasted with the Lyman continuum break at 912Å used by Steidel et al., which is strong for a young galaxy but very weak for an old one (figure 1). Thus these two breaks provide complementary selection methods, one biased towards blue active galaxies and one biased towards red passively evolving galaxies.

It is not necessary to produce customized filters (such as were used by Steidel et al.) to measure the strength of the 4000Å-break, so long as one is prepared to be limited to the redshifts for which the break falls between standard filters; for example, $z \sim 1.6$ for $I$ & $J$, $z \sim 2.7$ for $J$ & $H$, and $z \sim 3.8$ for $H$ & $K$. Figure 1 illustrates how the $J$ and $H$ filters approximately bridge the break for an evolved galaxy at $z = 2.39$. This led us to the idea of using near-infrared imaging to identify galaxies with a strong break on the basis of their infrared colours.

The target field chosen for this project was that around the radio galaxy 53W002, which has a redshift of 2.39. Hubble Space Telescope and ground-based searches for emission-line objects surrounding this galaxy revealed a total of eighteen potential cluster members. Spectroscopic redshifts of $z \approx 2.4$ have now been measured for several of these candidates (Pascarelle et al. 1996a,b). The compact size of these sources and their faint luminosities have suggested that they may be the subgalactic-sized progenitors of massive ellipticals or spirals.
Once again though, the selection technique used to find these sources is biased towards those galaxies with detectable Ly$\alpha$ emission, i.e. active or star-forming galaxies, and is insensitive to any passively evolving cluster members. The complementary search for such passive galaxies, reported here, will thus allow us to investigate the full range of star-formation activity in this cluster.

2. Observations

The field was observed at the 3.8m UK Infrared Telescope, Mauna Kea, Hawaii on 26–27 May 1995, using the near-infrared imaging camera IRCAM3, in reasonable weather and with seeing of 0.8–1.2 arcsec. A standard jittering procedure was used to obtain a median-filtered sky flat-field simultaneously with the data. Total exposure times of either 54 or 81 minutes were obtained in $J$, $H$ and $K$ across a field of $\sim100\times100\text{ arcsec}^2$.

Magnitudes for the sources were measured in a 3.5-arcsec diameter aperture. The reliability of the photometry was tested by two of us calculating magnitudes independently for a selection of faint sources across the field, and the results were found to be in good agreement. Our magnitudes for the radio galaxy ($J = 20.70 \pm 0.19$, $H = 19.77 \pm 0.28$ & $K = 18.81 \pm 0.12$) are also consistent with those of previous observations ($J = 20.70 \pm 0.28$, $H = 19.84 \pm 0.29$ & $K = 18.61 \pm 0.17$; Windhorst et al. 1994).

3. Results & Discussion

We detect a total of 42 objects in the $K$-band, of which 36 are above our 80% completeness limit. Of these 42 sources, we have isolated a sample of 10 galaxies with $J - H > 1.0$ and $K > 18.8$, that are redder and fainter than the radio galaxy, and consistent with the presence of a 4000Å-break at $z = 2.39$ (figure 2). Our selection criteria are based on the following: (i) radio galaxies can have a significant contribution to their blue flux arising from the embedded active nucleus, so we would expect any passively evolving galaxy at the same redshift, in the absence of an AGN, to possess a stronger 4000Å-break and hence have a redder colour; (ii) the radio galaxy has above-average optical luminosity ($L \approx L^*$, Windhorst et al. 1991), so we expect any companion galaxies to be comparable to, or fainter than, 53W002 in $K$ (rest-frame optical). The selection rules are illustrated on the colour–magnitude diagram as dotted lines.

Below we will compare the colours of our red cluster candidates with those predicted by spectro-photometric models of elliptical galaxies, but first we consider model-independent evidence that these ten sources are indeed part of the cluster. Most excitingly, the reddest and third reddest galaxies in our sample (objects A and B; denoted ‘19’ and ‘18’ in Pascarelle et al. 1996b) are the only two sources in the cluster, that are detected at $K$, which have been shown via optical spectroscopy to lie at the same redshift as the radio galaxy. The other spectroscopically confirmed members were either not detected in the $K$-band or lay outside the infrared field. The remaining eight of our ten red galaxies have not been identified as Ly$\alpha$ emitters, and are good candidates for passively evolving elliptical galaxies at $z = 2.39$, with significant breaks and, at most, weak Ly$\alpha$ emission. These extremely encouraging results show that (i) near-infrared
Figure 2. Colour–magnitude diagram for the 42 sources in the field detected at $K$. The radio galaxy is denoted by a box; spectroscopically confirmed members of the cluster by a hollow circle (A & B); and a star denotes a source which appears stellar on the HST image of Pascarelle et al. (1996b). Dotted lines show the criteria used to select potential cluster members ($J - H > 1.0$, $K > 18.8$).

Colours can indeed be used to successfully identify high-redshift galaxies on the basis of the strength of the 4000Å-break, and (ii) at least some galaxies possess a significant 4000Å-break at large lookback times, where most galaxies studied to date have been found to be relatively blue.

It is particularly interesting to compare these sources with those in the 2139–4434B1 group of Francis et al. (1997; also, this volume). Three galaxies (B1, B2, B4) at a redshift of 2.38 have been discovered via narrow-band Lyα imaging, and confirmed spectroscopically. B1 has the same infrared magnitudes as our object A, and (after making a correction for the AGN contribution in A) the two galaxies have comparable optical magnitudes. The colours of all three galaxies ($J - K = 2.1–2.8$) are also comparable to the four reddest of our sources ($J - K = 1.9–2.6$), although the mean colour of our sources is a little less at $J - K = 1.7$.

In figure 3 we present results of our modelling of the evolution of the second reddest of our cluster members, using an updated version of the spectral evolution models of Guiderdoni & Rocca-Volmerange (1987). Note that we use the second reddest source, as the reddest one, object A, is an AGN with >75% of its optical flux in an unresolved point source and 20–30% of its $K$ flux due to Hα emission — it’s red colour is unlikely to be due solely to an old stellar pop-
ulation. One of the simplest scenarios to consider is to assume that all the stars formed in a single burst of star-formation of 1 Gyr duration and then evolved passively. The strength of the 4000Å-break is then determined by the evolution of the main sequence turn-off mass. The $J-H$ colour of such a galaxy as a function of redshift is shown for galaxies of different ages (i.e. time after the cessation of star-formation) in figure 3.

It can be seen that at the cluster redshift, 53W002 has the colours of a 0.4 Gyr-old galaxy, in agreement with the age previously inferred from more detailed spectroscopic information (Windhorst et al. 1991). The second reddest source in our field is predicted to have an age of $1.1^{+1.0}_{-0.6}$ Gyr. For comparison, an Einstein-de Sitter universe is only $1.4h_{75}^{-1}$ Gyr old at this redshift.

An analysis of the infrared surface brightness profiles of the red galaxies shows that most of the sources are clearly resolved, with the notable exception of object A. Fitting the mean profile with a seeing-convolved de Vaucouleur’s model gives a scale length of $13 \pm 10h_{75}^{-1}$ kpc, significantly larger than the 0.5–1.0 kpc sizes of the Lyα-selected cluster candidates. All the infrared-selected galaxies and most of the optically-selected ones lie within one arcminute ($\sim 0.5$ Mpc) of
one another, the size of a group or small cluster of galaxies (see Waddington et al. 1997 and Pascarelle et al. 1996 for the respective images).

In June 1997, we observed seven of the red cluster candidates using the LDSS-2 multi-object spectrograph on the 4.2m William Herschel Telescope. A total of 40,000 seconds was obtained on each source, with seeing of $\approx 1.0''$. Preliminary results from a rough reduction of the first night of the data show that two of the sources have strong emission or absorption features that put them at $z < 1$. The other five targets have definite continuum detections visible in the two-dimensional images, but require careful sky subtraction before the reality of the spectral features can be confirmed. The inclusion in the selected sample of two low redshift sources is entirely consistent with the field contamination expected, and so far does not invalidate our selection technique.

In conclusion, we have discovered ten sources with red $J-H$ colours around the radio galaxy 53W002, that are consistent with the presence of a 4000Å-break at the cluster redshift. The ages of the galaxies deduced from the strength of the break are consistent with a 1 Gyr burst model of galaxy evolution, observed at ages of 0.4–1.1 Gyr. With the close proximity of these companions to one another and their relatively large size, the evidence suggests that 53W002 lies in a group or cluster that has already undergone significant evolution at $z = 2.39$.

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