Subaru Deep Near-Infrared Imaging of the Field of a Possible Proto-Cluster Near the Radio Galaxy 53W002 at z = 2.4

Toru Yamada, Kentaro Motohara, Fumihide Iwamuro, Toshinori Maihara, Masaru Kajisawa, Ichiro Tanaka, Tadayuki Kodama, Hiroshi Terada, Miwa Goto, Hiroisa Tanabe, Tomoyuki Taguchi, Ryuji Hata, Tadafumi Takata, Kazuhiro Sekiguchi, Masanori Iye, Toshiyuki Sasaki, Tomonori Usuda, George Kosugi, and Chris Simpson

Astronomical Institute, Tohoku University, Aoba-ku, Sendai, Miyagi 980-8578
National Astronomical Observatory, 2-21-1, Osawa, Mitaka, Tokyo 181-8588
Department of Physics, Faculty of Science, Kyoto University, Sakyo-ku, Kyoto 606-8502
Subaru Telescope, National Astronomical Observatory of Japan, 650 North Aohoku Place, Hilo, HI 96720, U.S.A.
Department of Astronomy, School of Science, The University of Tokyo, Bunkyo-ku, Tokyo 113-0033

(Received 2001 May 22; accepted 2001 September 3)

Abstract

We present the results of deep K′- and J-band imaging of the field of a proto-cluster region near the radio galaxy 53W002 at z = 2.390 with the Subaru Telescope. The data were analyzed together with deep optical and near-infrared (NIR) images taken with the Hubble Space Telescope to investigate the properties of ten optically compact emission-line galaxies and candidates. Excluding the three objects which may contain active galactic nuclei, many are faint or undetected at K′ (λ_{rest} ≈ 6000 Å), and are therefore revealed to be intrinsically small starbursting objects. On the other hand, we detect few objects with colors and magnitudes expected for quiescent massive galaxies at z = 2.4 in the field.

Key words: galaxies: active — galaxies: elliptical and lenticular, cD — galaxies: evolution

1. Introduction

Pascarelle et al. (1996a,b) detected more than ten Lyα emission-line galaxies and candidates at z ~ 2.4 in the field of the moderately powerful z = 2.39 radio galaxy 53W002 (Windhorst et al. 1991) through HST intermediate-band observations. Six of these objects have since been confirmed to lie at the same redshift as the radio galaxy. The compact morphologies of these objects in the F606W HST image led Pascarelle et al. to argue that these objects are subgalactic ‘building blocks’ which will merge into a larger system. However, the HST F606W observations probe only λ_{rest} ≈ 1800 Å and the continuum emission could therefore be dominated by high-surface brightness star-forming regions. Near-infrared imaging is important to constrain the existence of developed stellar systems in these optically compact objects.

Keel et al. (1999) performed narrow- and intermediate-band imaging over a wider field around 53W002. They found a significant excess of emission-line objects, and six of their 14 candidates have been confirmed to lie at z = 2.4. It is therefore quite plausible that this region represents a density peak in the large-scale structure at this epoch and the high galaxy density might indicate a protocluster. It is thus important to see if any massive galaxies have already formed in this region, or if only compact small emission-line objects are clustered. Passively evolving old galaxies have very conspicuous optical–NIR colors at intermediate and high redshift (e.g., Yamada, Arimoto 1995; Dickinson 1995; Yamada et al. 1997) and can be separated from the numerous foreground galaxies by their colors. Thus, deep NIR observations are essential to detect and study such evolved massive galaxies.

With these purposes in mind, we obtained deep K′- and J-band images of the field around 53W002 during the commissioning period of the 8.2-m Subaru Telescope. We describe our observations and data reduction in section 2 and consider the overall color and magnitude distributions of the galaxies in the field in section 3. The images, morphology, spectral energy distributions (SEDs) of the emission-line galaxies and candidates are presented in section 4. We then further discuss the nature of the objects in this interesting field in the last section. We use a conventional set of cosmological parameters, H_0 = 50 km s^{-1} Mpc^{-1}, q_0 = 0.5, \lambda_0 = 0, throughout this paper unless otherwise noted.

2. Observations and Data Reduction

The 53W002 field was observed in the K′- and J-band with the 8.2-m Subaru Telescope equipped with the Cooled Infrared Spectrograph and Camera for OHS (CISCO; Motohara et al. 1998) on 1999 April 4/7 (UT) and May 26 (UT) for the K′-band and the J-band, respectively, during the telescope commissioning period. The detector used was a 1024×1024 HgCdTe array with a pixel size of 0′′116, which provides field of view of ~2′×2′ per frame. The total net exposure time was...
4880 s in $K'$ and 3840 s in $J$. The weather conditions were stable during the observations and seeing was $\sim 0''.3 - 0''.5$.

The data were reduced using the IRAF software package.\footnote{The Image Reduction and Analysis Facility (IRAF) is distributed by National Optical Astronomy Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.}

The procedure was similar to that adopted in previous studies using CISCO (e.g., Kajisawa et al. 2000); we only briefly describe the data reduction here.

We first subtracted the bias component. The bias level varied during the observations, leaving a residual pattern which was not flat, resulting in a $10-20\%$ discontinuity in the background level of each frame across the central column of the detector. In the first and the second frames of the series of twelve exposures taken at each position, the residual was larger than that in later frames. We constructed a ‘template’ bias frame by averaging the third to twelfth frames and subtracting this from the average of the first and second frames. A scaled version of this template was then subtracted from every frame. The median sky background was subtracted using a master flat of many frames constructed by the CISCO team (see Iwamuro et al. 2000 and Maihara et al. 2001). The difference compared to flat-fielding with a median-filter of CISCO is very faint magnitudes ($<3$) diameter aperture at the position of the object in the $K'$-band. The r.m.s. fluctuation of the background sky in such an aperture after masking out the detected objects in the image of each band was used to estimate the photometric error.

3. Photometric Properties of the Objects in the Field

Figures 1 and 2 show $V_{606} I_{814} K'$ three-color image and $K'$-band monochromatic image of the field, respectively. Ten of the emission-line objects and candidates in Pascarelle et al. (1996b) lie in the CISCO field, and are shown by the arrows. #60 and #61, shown by the open arrows in figure 2, are not detected in the $K'$-band image. #6 (53W002), #12, #18, and #19 have spectroscopically confirmed redshifts, and are known to be at $z = 2.4$ (Pascarelle et al. 1996b), while #13 has turned out to be a star. An active galactic nucleus exists at least in 53W002 (radio galaxy). #19 (a broad-line object), and possibly in #18.

Motohara et al. (2001a, b) show the rest-frame optical spectra of these three objects.

Figures 3 and 4 show the $K$- and $J$-band number counts. The dashed histograms show the incompleteness-corrected counts, while the crosses show the counts obtained in the Subaru Deep Field (Maihara et al. 2001). There is good agreement, except at very faint magnitudes ($K > 22$), where we are $\langle 50\%$ complete and the counts in the 53W002 field systematically exceed those in the SDF. While we may have underestimated the completeness (see section 2), we note that the faint-end counts in SDF are slightly lower than that in other fields (Maihara et al. 2001).

Figures 5a and b show $I_{814} - K$ vs. $K$ and $J - K$ vs. $K$ color–magnitude diagrams of the $K'$-selected objects. The dashed lines indicate the nominal 2$\sigma$ detection limits in the $I_{814}$- and $J$-bands.

The overall $I_{814} - K$ color–magnitude distribution of the objects is similar to that of the objects in the Hawaii deep survey (Cowie et al. 1995) and in the Hubble Deep Field. At $K_{AB} \sim 22$ mag, the $I_{814} - K$ colors of the galaxies show conspicuous bluing, while there is also a relatively small number of faint
red objects. Many objects have $I_{814} - K_{AB} = 0 - 1.5$, while only a small number have $I_{814} - K_{AB} > 2$; there may be a possible ‘void’ in the color–magnitude distribution at $K_{AB} \sim 22.5$ and $I_{814} - K_{AB} \sim 1.5$. In fact, a similar trend can be seen in the Hawaii deep-survey data (Cowie et al. 1995) or in the HDF (Yamada et al., in preparation). Cowie et al. (1995) have already argued that galaxies which are blue in $I - K$ dominate the population at $K = 20.5 - 21.5$, while there is only a small number of objects with $I - K > 3$ (i.e., $I_{814} - K_{AB} \gtrsim 1.6$).

We also compare our $J - K$ vs. $K$ color–magnitude diagram with that of the Subaru Deep Field shown in figure 12 of Maihara et al. (2001). There is good agreement between the two sets of data. The median $J - K$ color of the SDF galaxies is $\sim 1.3$ (thus $J - K_{AB} \sim 0.2$) at $K = 20 - 22$ and there seems to be a sequence of objects with $J - K \sim 2.0$ ($J - K_{AB} \sim 0.9$) at the bright end, which is also seen in figure 5b. The bluing trend for the faint galaxies, which is seen in the $I_{814} - K$ vs. $K$ diagram, is also seen in the $J - K$ diagram. Many objects have $J - K_{AB}$ ranging from $-0.5$ to 1 while only a small number of them have $J - K_{AB} > 1$ at $K_{AB} > 22$ mag.
4. NIR Properties of Emission-Line Galaxies and Candidates

4.1. Origins of the $K'$- and $J$-Band Light

At $z = 2.4$, the H$\alpha$, N$\text{II}$, and S$\text{II}$ lines are redshifted into the $K'$-band and the O$\text{II}$ line into the $J$-band. Before discussing the NIR flux and light distribution of the emission-line galaxies and candidates, we evaluate the contributions to the $K'$- and $J$-band broad-band magnitudes from these lines.

Motohara et al. (2001a, b) have directly measured the emission-line contamination for objects #6 (53W002), #18, and #19. The contributions to the $J$ and $K'$ magnitudes, respectively, are 23% and 42% for 53W002, 11% and 32% for #18, and 4% and 29% for #19. Note that 53W002 is a radio galaxy while #19 is a broad-line AGN.

We crudely estimate the emission-line contamination in the other objects by considering their star-formation histories. For simplicity, we assume no dust extinction and a fixed IMF. The rest-frame UV continuum luminosity is proportional to the current star-formation rate (SFR) since the UV flux is dominated by short-lived massive stars, while at rest-frame optical wavelengths there is a contribution from older stars, and therefore the optical continuum flux depends on the SFR history as well. On the other hand, the emission-line luminosity is always proportional to the current SFR. For a constant SFR, for example, the ratio of emission-line to optical continuum luminosity is a monotonically decreasing function of time.

Using models constructed with the evolutionary synthesis code GISSEL96 (Bruzual, Charlot 1993), we estimate the emission-line contamination in the $K'$-band for the other
Fig. 3. Number counts of the $K'$-selected objects. The dashed histogram shows the counts after being corrected for the detection incompleteness in the $K'$-band frame. The crosses are the counts from the results of Subaru Deep Field (Maihara et al. 2001). Note that the magnitude values are those of the standard system, and no color correction is made in evaluating the $K$-band magnitude of the objects in our data.

Fig. 4. Same as figure 3, but for the $J$-band.

Fig. 5. Color–magnitude diagram of the $K'$-selected objects; $I_{814} - K$ vs. $K$ (panel a) and $J - K$ vs. $K$ (panel b). The blue circles indicate the emission-line galaxies and candidates at $z = 2.4$ in Pascarelle et al. (1996b) that are detected on our $K'$-band image. The dashed lines indicate the detection limit in $I_{814}$- and $J$-band represented by 2σ sky fluctuation with the photometric aperture over the frame. Those with a magnitude error less than 0.4 mag are shown with the filled dots and those with a larger error are by the open dots. All of the magnitudes and colors are given by the AB magnitude scale. Sequences of the passively-evolving galaxy models with various formation redshifts are also plotted (see text in section 4; the ages are those at $z = 2.4$). The open squares indicate the models with different luminosity when they evolve to $z = 0$, from $M_V = -23$ to $-17$ with one magnitude interval.
emission-line objects and candidates in the field of 53W002. We assume a constant SFR with a Salpeter initial mass function and solar metallicity. We calculate the flux ratio between rest frame UV (at 1500 Å) and optical (at 6500 Å and 3200 Å) wavelengths and use the relation between UV and Hα luminosity and SFR given in literature (e.g., Glazebrook et al. 1999). We assume line ratios of Hα/[O II] = 3, Hα/[N II] = 4, and Hα/[S II] = 6.

According to our models, the contributions from the emission lines at 10 Myr are 60% and 5% in K′ and J, respectively, falling to 30% and 4% at 100 Myr. If the age of star formation is larger than 100 Myr, the contribution is small and can be neglected in the following discussion. In the real data, we assume that the emission-line contamination can be as large as these values unless there is a strong AGN component, as in the case of 53W002 or object #19, and possibly for #18.

4.2. Comparison between Optical and NIR Light Distributions

In figures 6a and b, we show close-ups of the emission-line objects and candidates from Pascarelle et al. (1996b) at B450, V606, I814, J, and K′. The CISCO NIR images obviously have less spatial resolution than the optical HST images (0.′′4 compared to 0.′′16). Many of the objects are very faint in the NIR images, while objects #60 and #61 were not detected at all. In addition, #113 lies outside of the J-band frame, but is just visible in the K′-band image.

The three brightest objects in the K′-band image, namely 53W002, #18, and #19, are resolved in the CISCO images. Contour maps of the objects are shown in figures 7a–c. 53W002 has a similar elongation in the NIR images as in optical HST images, indicating a NIR alignment effect which may be due to the O II (J-band) and Hα (K′-band) emission lines. Lyα is known to be more extended than continuum emission (Windhorst et al. 1991).

There is an interesting emission feature extended toward the north of object #18. Its 'conical' structure is clearly seen in the optical images, and the counterpart is also seen in the NIR images, although it is slightly marginal in the J-band one. Keel et al. (1999) also found much more extended Lyα emission north of the object, with an opening angle and direction somewhat similar to those of the structure seen in the broad-band images. We therefore suppose that the extended structure is likely to be associated with #18. In the K′-band images, there may be a significant contribution by the Hα emission line, since the structure seems to be more prominent than in the J-band with similar detection threshold. The nature of this object is not yet fully understood, and it may contain an AGN, since there is a weak C IV line in the UV spectrum.

Object #19 is known to be a broad-line AGN, and is marginally resolved in the HST images. It is well-resolved in the K′ image; this is unlikely to be due to Hα, since the F450W image (which contains Lyα) is not as extended. The extension we see at K′ is therefore most likely to be due to stellar emission from the host galaxy.

4.3. Radial Light Distribution

In figure 8, we show photometric curves of growth of the emission-line objects and candidates at K′. The dotted line indicates the MAG BEST value from SExtractor. In figure 9, we compare the central parts of these curves of growth with that of a star in the field matched at the most inner radius.

As shown in the previous subsection, 53W002 and objects #18 and #19 are clearly extended, while #5 and #12 are marginally extended, and #10, #11, and #113 are not resolved at our 0.′′4 (3 kpc; 5 kpc if q0 = 0) resolution. Thus, these unresolved, or only marginally-resolved, objects appear to be small with a size of the present-day dwarf galaxies, while our
Fig. 7. Surface-brightness contours for the three NIR bright objects, 53W002 (upper left), #18 (upper right), and #19 (lower left), in the HST $B_{450}$-, $V_{606}$-, $I_{814}$-, and CISCO $J$- and $K'$-band images. Contours for a star in the same frame are shown in the inset for reference.
Fig. 8. Radial photometric curve of growth for the ten emission-line objects and candidates on the $K'$-band image. The dashed lines indicate the pseudo total magnitude (MAG BEST value) obtained using the SExtractor package. Note that we refer to the optical position for #60, #61, and #113 that are not detected in the $K'$-band.

nominal r.m.s. value of the pixel count fluctuation corresponds to 27.5 mag in the $K'$-band; the existence of smooth extended structures below the detection limit cannot be ruled out.

4.4. Spectral Energy Distribution of the Objects

In figure 10, we also show the optical–NIR observed spectral energy distributions (SEDs) of the ten emission-line objects. For a comparison, we show the $f_\lambda \propto \lambda^{-2}$ (or $f_\nu = \text{constant}$) spectrum by the dotted line in the figure for object #5. Except for the three brightest objects (53W002, #18, and #19), many of the galaxies have very blue SEDs. If we correct the NIR fluxes for emission lines (see subsection 4.1 above), the optical–NIR slope of the SED becomes slightly steeper, although the $B$-band flux should be reduced to correct for Ly$\alpha$ emission. If these objects are at $z \sim 2.4$ (note that #12 has a confirmed redshift) they may be genuinely young starbursting objects.

The SEDs of the three bright objects seem to be different from those of the other seven objects. Their redder SED may be due to the larger contribution by the stellar light in the $K'$-band. Indeed, Motohara et al. (2001a) provide detailed modeling of the 53W002 SED based on their spectroscopic data, and conclude that the stellar light is dominated by stars which are a few hundred Myr old.
5. Discussions

5.1. Color Distributions in the Field

Keel et al. (1999) discovered a larger-scale concentration of emission-line objects. The 53W002 field may therefore be a part of the Universe which will evolve into a region of high galaxy density, possibly a cluster of galaxies at a later epoch.

At intermediate redshifts, $z \lesssim 1$, it is well established that rich clusters of galaxies are dominated by old early-type galaxies, although the fraction of blue galaxies increases with the redshift. Most of the stars in the early-type galaxies must have formed at redshifts $z \gtrsim 2$–3 (e.g., Aragón-Salamanca et al. 1993; Stanford et al. 1998; Kodama et al. 1998). The redshift of 53W002 thus makes it worthwhile to investigate whether there are any evolved massive galaxies in the putative protocluster, or whether there are just small starbursting objects and/or young galaxies. $J$ and $K'$ images are essential for this purpose, since these two bands bracket the 4000 Å break and Balmer jump for galaxies at $z = 2.4$.

Figures 5a and b also show the color–magnitude relations of cluster galaxies as expected from the Coma cluster model of Kodama et al. (1998), assuming five different formation redshifts. This model uses the color–magnitude relation of the Coma cluster to predict the metallicity sequence of cluster galaxies at higher redshift, and has successfully explained the evolving color–magnitude sequence in intermediate-redshift clusters. The open squares corresponds to those models with $M_V = -23$ to $-17$ at $z = 0$, with an interval of one magnitude.
While all five models converge at $z \lesssim 1$, they show large differences at $z = 2.4$. It is clearly seen that there are no luminous passively-evolving galaxies older than 0.5 Gyr at $z = 2.4$ in this field. With the adopted cosmological parameters, this means that no such quiescent galaxies formed at $z \gtrsim 3.5$ and have passively evolved.

We now consider the two-color diagrams of the objects in the field to compare the various evolutionary synthesis models observed at different redshifts. Figures 11a and b show an $I_{814} - J$ vs. $J - K$ two-color diagram compared with models with old ($z_\text{f} = 4.4$) and young ($z_\text{f} = 3.0$) ages at $z = 2.4$. While some objects have colors consistent with $z = 2.4$ galaxies with significant star formation, we again see that there are few objects with the colors of quiescent passive galaxies.

Finally, we speculate on the curious color distribution of $K_{\text{AB}} > 22$ galaxies, namely the large number of blue galaxies and small fraction of very red galaxies. If this represents a general trend for faint galaxies, and is not due to an artificial effect, such as photometric contamination from faint blue galaxies which are undetected in the NIR images, it may constrain the global galaxy formation history. Recently, studies of the HDF have revealed that the number density of evolved early-type galaxies decreases sharply at above $z > 1$ (Franceschini et al. 1998; Dickinson 2000; Kajisawa, Yamada 2001). It is therefore not surprising that we see few developed quiescent galaxies at $z \sim 2$ in the 53W002 field. Although we do not
know whether the region will develop into a cluster at a later epoch, the study by Keel et al. (1999) clearly indicates that the region is part of a large-scale structures at $z = 2$. The study by Keel et al. (1999) clearly indicates that the distribution could therefore indicate that the formation of large early-type galaxies had not occurred by $z \sim 3$ even in such high density region at the field of 53W002. Deep NIR imaging covering a wider field is thus desirable to reach a firm conclusion on this matter.

5.2. Nature of the Three NIR Bright Objects

The extended nature of objects #18 and #19 as well as 53W002 suggests that they may be galaxies with developed young stellar systems. In figures 5 and 11, we show the candidate emission-line galaxies by the blue circles. The three bright objects have $I_{814} - K_{AB} \sim 2$ and $J - K_{AB} \sim 0.9$; these colors are consistent with a few hundred Myr-old stellar population after taking the emission-line contributions (see subsection 4.1) into account, although we have not evaluated how much contribution by the AGN continuum exists in the colors of object #19.

Motohara et al. (2001a) detected a Balmer jump in the NIR spectrum of 53W002, and clearly showed that the stellar light is dominated by such a young stellar population, as originally suggested by Windhorst et al. (1991). It is interesting to note that the three most NIR-bright objects among the emission-line-selected objects at $z = 2.4$ appear to harbor AGN (definitely in the cases of 53W002 at #19, and possibly for #18).

We have already commented on the conical feature apparently associated with #18, which could be predominantly due to emission lines. Future NIR spectroscopy should resolve this issue, and may shed light on the origin of the large emission line blobs seen at high redshift (Keel et al. 1999; Steidel et al. 2000). Suggested models for such objects include photoionization by AGN or starbursts (e.g., Steidel et al. 2000), excitation by heating in the gravitational collapse (Haiman et al. 2000), and resonance scattering for Ly$\alpha$ emission. The Ly$\alpha$/H$\alpha$ ratio can discriminate these models.

Object #19 is obviously a type-1 AGN. However, the $K'$-band image is clearly resolved and at least 40% of the $K$-band light is from the extended component. If the emission is from the host galaxy, its absolute magnitude corresponds to $M_{6500} = -23.4$ mag, and it is therefore a fairly luminous object.

5.3. Blue Emission-Line Galaxies and Candidates

Among the ten emission-line-selected objects, seven galaxies show a very compact morphology and a blue SED. In this subsection, we discuss the nature of these objects assuming that they are all at $z = 2.4$, although only one has been spectroscopically confirmed to lie at this redshift.

We compare the observed SEDs of these objects with models to constrain their star-formation history. The seven blue galaxies have $-0.2 < V - K_{AB} < 0.6$, which can be explained by populations with ages of 0.1–1 Gyr and a constant SFR. This age can be reduced with fairly moderate extinction; for a Galactic extinction curve with $A_V \sim 0.3$ mag, the color can be reproduced with a 50–100 Myr-old population.

Figure 12 shows a histogram of the rest-frame $R$-band magnitudes of the seven blue emission-line objects, plus 53W002 and objects #18 and #19. Six of the seven blue objects have $M_R(AB) > -21.5$ ($-22.4$ for $q_0 = 0$), compared to $M_R = -21.6$ for a local $L_\star$ galaxy (Lin et al. 1996). Note that accounting for passive evolution makes the $z = 2.4$ objects even fainter compared to a present day $L_\star$ galaxy. In addition, since these galaxies are dominated by young stellar populations with a low mass-to-light ratio, they must be much less massive in stellar mass.
components than the present-day $L_*$ galaxies, consistent with their small sizes (subsection 4.3). Although the NIR results presented here suggest that these objects are truly young, less-massive (at least in stellar component) systems, are they really the ‘building blocks’ of massive galaxies, as suggested by Pascarelle et al. (1996a, b)? It is not clear what are the present-day counterparts of these objects. Although more systematic wide-field observations over a wider redshift range are required, it is interesting to note that there are few galaxies in the field whose colors and magnitudes are consistent with those expected for passively-evolving massive galaxies, and the stellar populations of the galaxies at $z = 2.4$ seem to be as young as $\sim 0.5$ Gyr. If this field of 53W002 will evolve into a central region of a cluster of galaxies at later epoch, a number of progenitors of the giant early-type galaxies in clusters have concluded that they must have formed before $z \sim 2–3$ (Aragón-Salamanca et al. 1993; Stanford et al. 1998; Kodama et al. 1998). Since there are a few candidates in the 53W002 field that could be fully developed systems, it appears that we are observing this region either during, or just before, the time when most of the galaxy formation takes place. In this broad sense, it may be plausible that these emission-line objects are indeed the progenitors of present-day massive galaxies.

Finally, we also compare the NIR nature of these objects with other high-redshift galaxies. At $z \gtrsim 2$, a number of Lyman Break Galaxies (LBGs) are known to exist. In the Hubble Deep Field, Sawicki and Yee (1998) compiled the photometric properties of the two samples of LBGs (Steidel et al. 1996; Lowenthal et al. 1997). The four spectroscopically-confirmed LBGs in HDF at $2.2 < z < 2.6$ have $23.7 < K_{AB} < 24.6$ (Sawicki, Yee 1998), similar to those detected here. Their observed $V_{606} - K$ colors are between 0.1 and 0.6, also similar to those of the emission-line galaxies in the 53W002 field.

6. Summary

We have presented the results of deep near-infrared imaging of the field around the $z = 2.39$ radio galaxy 53W002. Combined with archival HST optical data, we find that, apart from the three objects which are known or appear to contain AGN, the emission-line galaxies are blue and intrinsically faint in the rest-frame $R$-band. Combined with the presence of very few objects with colors and magnitudes consistent with those of passively-evolving massive galaxies, we suppose that we are observing this protocluster of galaxies early during its period of galaxy formation.

This paper is based on data collected using the Subaru telescope, which is operated by the National Astronomical Observatory of Japan. This research was supported by grants-in-aid for scientific research of the Ministry of Education, Culture, Sports, Science and Technology (08740181, 09740168). This work was also supported by the Foundation for the Promotion of Astronomy of Japan. T.K. thanks Japan Society for the Promotion of Science for financial support through its Research Fellowships for Young Scientists. This work is based in part on observations with the NASA/ESA Hubble Space Telescope, obtained from the data archive at the Space Telescope Science Institute, U.S.A., which is operated by AURA, Inc. under NASA contract NAS5–26555. The Image Reduction and Analysis Facility (IRAF) used in this paper is distributed by National Optical Astronomy Observatories, U.S.A., operated by the Association of Universities for Research in Astronomy, Inc., under contact to the U.S.A. National Science Foundation.

References

Dickinson, M. 1995, in ASP Conf. Ser. 86, Fresh Views of Elliptical Galaxies (San Francisco: ASP), 283

Fig. 12. Distribution of the rest-frame absolute magnitude, $M_{AB}$, at 6500 Å for the ten objects. #60 and #61 are not detected in the $K$-band image and the obtained magnitude of #113 is fainter than our nominal detection limit of the $2\sigma$ sky fluctuation with the photometric aperture. The upper limit of absolute magnitude of the three objects are evaluated by using the nominal detection limit.
No. 6] Possible Proto-Cluster Near the Radio Galaxy 53W002 at z = 2.4