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# A HERO in the Field near 53W002

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## Abstract

HEROs (Hyper Extremely Red Objects) are objects which are very red in NIR colors ($J-K \gtrsim 3$). They are speculated to be intrinsically red galaxies at $z \gtrsim 2$ or Lyman-break galaxies at $z > 10$. We report the discovery of a HERO in the field which includes a known radio galaxy, 53W002, and a possible cluster of galaxies both at $z = 2.39$. The HERO, which we name as HERO J171411.91+501541.8, or 53W002-HERO1 for brevity, is visible in the HST NICMOS $H$-band data and deep $K'$-band data from Subaru telescope ($K' \simeq 21.5$ mag), but not visible in $B$, $V$, $I$, and $J$ band images ($J-K > 4.45$, 2-$\sigma$). Its spectral energy distribution is consistent with that of a dusty starforming or an old galaxy at $z \simeq 2.4$, which may suggest that 53W002-HERO1 is a member of group of galaxies associated with 53W002. Alternatively, the HERO could be at $z \simeq 12.5$, if its red color is due to the redshifted Lyman break. If 53W002-HERO1 is an old galaxy at $z \sim 2.4$, the implied stellar age is a few Gyrs, meaning that stars in the HERO formed at the reionization epoch of $z \gtrsim 10$.


## 1.1 Introduction

Extremely Red Objects (EROs) are objects with very red optical-NIR color ($R-K > 5-6$ mag or $I-K > 4-5$ mag; Elston, Rieke, & Rieke 1988; Graham & Dey 1988; Hu & Ridgeway 1994; Soifer et al. 1994; Thompson et al. 1999; Yan et al. 2000; McCarthy et al. 2001; Roche et al. 2002; Smith et al. 2002). The color of $R-K > 5$ corresponds to the color of passively evolving early-type galaxies at $z \gtrsim 1$ in observed frame. Studies have shown that most EROs are either early-type galaxies at $z \gtrsim 1$ or dusty starforming galaxies/AGN's at similar redshift (Cimatti et al. 2002). Their number density has been studied to constrain the formation epoch of early-type galaxies (Daddi et al. 2000; Chen et al. 2002) which appears to be at $z > 1$ according to the results from optical data (e.g., Im et al. 2002). HEROs are the reddest objects among EROs, with very red NIR colors (Totani et al. 2001). While the majority of EROs have a NIR color of $J-K \lesssim 2$ mag, HEROs have $J-K > 3$ mag. They tend to be faint in $K$ ($K \gtrsim 21$ mag), and not detectable or only marginally detectable in $J$ and optical bands. Because HEROs are rare and have extreme colors, only a handful of HEROs have been discovered so far (Bershady, Lowenthal, & Koo 1998; Dickinson et al. 1999; Mohan et al. 2002; Hall et al. 2001; Smail et al. 1999).

Here, we report the discovery of a HERO — HERO J171411.91+501541.8 or 53W002-HERO1 for brevity — in the field near a radio galaxy 53W002 at $z = 2.39$ (Windhorst et al. 1998). Previous observational evidence suggests that there is a cluster of galaxies at $z \sim 2.4$

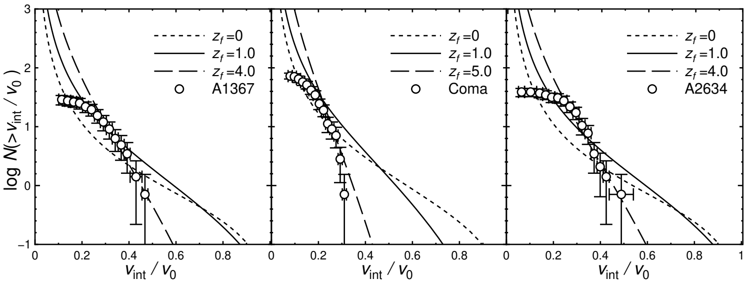


Fig. 1.1. Postage stamp images of 53W002-HERO1 in $B$, $V$, $I$, $J$ (HST), $J$ (Subaru), $H$ (HST), and $K'$ (Subaru). North is up and east to the left. Each side of the image is 8.″0 long. The object is visible in $H$ and $K'$ images, but is not detected in $J$ and bluer passbands.

in the 53W002 field (e.g., Pascarelle et al. 1996). Our discovery marks the first detection of a HERO in the field of a known $z > 2$ cluster of galaxies candidate, which may help understand the nature of HEROs.

## 1.2 Data

53W002-HERO1 was discovered from deep Subaru $J$ and $K'$ images (Yamada et al. 2001), and HST NICMOS $J_{110}$ (F110W) and $H_{160}$ (F160W) band data of the 53W002 field (Keel et al. 2002). The HST NICMOS data were obtained from the STScI archive, and reprocessed to correct for the pedestal effects, and then stacked to create a deeper image. 53W002-HERO1 is located in the overlapping region between two NICMOS pointings, and the total exposure time per pixel amounts to 4894 seconds for each band. The Subaru data were obtained with CISCO (Motohara et al. 2002) in April and May 1999 during the telescope commissioning period. The total net exposure time was 4880 sec in $K'$ and 3840 sec in $J$. The 5 $\sigma$ detection limits within 1-arcsec diameter apertures are 23.7 mag and 22.5 mag in $J$ and $K'$ band data respectively. For more detailed description, see Yamada et al. (2001). In addition to the NIR data, we also analyzed the HST WFPC2 archive data of the 53W002 taken by Windhorst et al. (1998) in $B_{450}$ (F450W), $V_{606}$ (F606W) and $I_{814}$ (F814W). These data are very deep — only about 1 mag shallower than the depth of the Hubble Deep Field.

Figure 1 shows postage stamp images of 53W002-HERO1 in $B_{450}$, $V_{606}$, $I_{814}$, $J_{110}$, Subaru $J$, $H_{160}$ and Subaru $K'$. The size of each image is 8.″0 by 8.″0. The postage stamp images show that 53W002-HERO1 is visible only in the $H$ and $K'$ bands. The FWHM of 53W002-HERO1 is 0.″5 while that of stars in the NICMOS image containing 53W002-HERO1 is about 0.″35. We measured the major axis half light radius ($r_{hl}$) using the 2-dimensional surface brightness profile fitting program, GIM2D (Simard et al. 2002). Our measurement indicates $r_{hl} \sim 0.''4 \pm 0.''2$ for 53W002-HERO1. Note that, for a star in the same field, $r_{hl} \sim 0.''06$ — the practical measurement limit for a point source in an image with the pixel size of 0.″2. Therefore, 53W002-HERO1 is not a point source like exotic stars.

## 1.3 Discussion

Figure 2 shows the SED of 53W002-HERO1 (points and arrows). The observed SED is compared with SEDs of the following three objects: (1) solid line – a 3.0 Gyr old passively evolving galaxy at $z = 2.39$ (0.1 Gyr burst with formation redshift, $z_{form} \simeq 10$, the

Salpeter IMF, and 2.5 times solar metallicity, and the cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65$ km sec$^{-1}$ Mpc$^{-1}$); (2) dotted line – a dusty galaxy, HR10 (Hu & Ridgeway 1994), redshifted to $z = 2.39$; and (3) dashed line – starforming galaxy at $z = 12.5$ with no internal dust extinction, but with intergalactic extinction due to neutral hydrogen. The observed broad-band SED of 53W002-HERO1 is roughly consistent with all the above reference SEDs. The $J$-band data appear to fall below the reference lines of (1) and (2), although we get a better match with the more conservative $J$-band upper limit of 0.19 $\mu$Jy.

If 53W002-HERO1 is a Lyman-break galaxy at $z = 12.5$, the observed $K$-band flux, corresponding to the rest-frame UV flux, suggests a star formation rate of order 200 $M_\odot$ yr$^{-1}$ assuming no dust extinction (e.g., Dickinson et al. 1999). Then, the object would have a stellar mass of $10^{10}$ – $10^{11}$ $M_\odot$ with a short starburst of order of $10^8$ — $10^9$ Gyrs.

Several works argue that an object like HERO is more likely to be a dusty object rather than an old object at $z \sim 2$ or a Lyman-break galaxy at $z > 10$ (e.g., Totani et al. 2001). If 53W002-HERO1 is a dusty galaxy at $z \sim 2.4$ similar to HR10, the rest-frame luminosity in the optical and the UV suggests it is about 10 times fainter than HR10. By rescaling the properties of HR10 (Dey et al. 1999), we estimate that 53W002-HERO1 has a stellar mass of $\sim 10^{10}$ $M_\odot$, a star formation rate of $\sim 100$ $M_\odot$ yr$^{-1}$, and an extinction of about $A_V = 4.5$ mag.

If 53W002-HERO1 is an old galaxy at $z \sim 2.4$, its stellar age is about 3.0 Gyrs assuming the model (1). The corresponding formation redshift is $z \gtrsim 10$, the epoch when the IGM contained a significant amount of neutral hydrogen (Fan et al. 2001; Djorgovki et al. 2001). Therefore, the stars in 53W002-HERO1 could be typical of the sources that reionized the universe. From the luminosity and SED, we estimate that the stellar mass of the HERO is $\sim 10^{10} - -10^{11}$ $M_\odot$ at $z = 2.39$. This corresponds to the total mass of $10^{12}$ $M_\odot$ or more assuming that stellar mass is one percent of the total halo mass.

The apparent $r_{hl}$ of $0\farcs4$ corresponds to a physical size of 1.5 kpc at $z = 12.5$, and 3.3 kpc at $z = 2.4$. According to Figure 5 of Im et al. (2001), the $r_{hl}$ of 1.5 kpc corresponds roughly to $r_{hl}$ of $10^{10}$ — $10^{11}$ $M_\odot$ nearby E/S0 galaxies. This number is consistent with the stellar mass estimated from the $K$-band flux assuming $z = 12.5$, making it difficult to exclude this “ultra high-z” hypothesis based just on the size and luminosity.

53W002-HERO1 is located about $30''$ away from 53W002 and within the field covered by the Lyman-$\alpha$ emitters at $z \sim 2.4$ (Pascarelle et al. 1996). If 53W002-HERO1 is associated with the $z = 2.4$ cluster of galaxies candidate, one would naively expect that the 53W002 field contains more HEROs than other randomly chosen fields. Unfortunately, very deep observations of field galaxies in both $J$ and $K'$ are rare and generally cover fields of view (FOV) of only a few $\Box'$. More data are clearly needed to establish any connection between HEROs and high redshift cluster of galaxies.

## 1.4 Future Prospects

In Figure 3, we show the SED of 53W002-HERO1 with model lines extending to longer wavelengths. The redshifted line of HR10 is extended to longer wavelengths using the model of Chary & Elbaz (2001), which fits the real HR10 data at FIR, submm, and radio. Also plotted in Figure 3 are 5-$\sigma$ detection limits of deep SIRTF, SCUBA, and VLA observations (a few hours or more). SIRTF detection limits are uncertain by a factor of a few, and our number is somewhere between the most optimistic and the most pessimistic cases (e.g., Väisänen, Tolestrup & Fazio, 2001; Xu et al. 2001). The SCUBA limits come

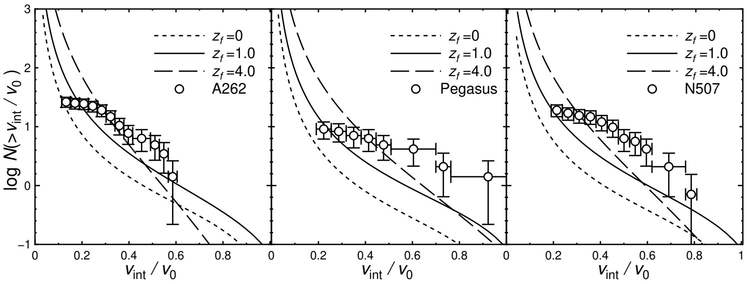


Fig. 1.2. The observed SED of 53W002-HERO1, compared with three reference SEDs (solid line: old galaxy at $z = 2.39$, dotted line: dusty galaxy at $z = 2.39$, and dashed line: Lyman break galaxy at $z = 12.5$). The observed SED is consistent with all the reference SEDs plotted. The $H$ and $K'$-band points are presented with 2-$\sigma$ errors.

from Blain, Ivison, & Smail (1998) and the VLA limits are from the deep VLA observation of HDF by Richards et al. (1998).

Lyman break galaxies at $z \sim 12.5$ will have a flat SED with flux density of $\sim$1 $\mu$Jy at 3-8 micron, while intrinsically red objects at $z \sim 2$ will have a SED which steeply rises toward longer wavelengths above a few $\mu$Jy. The 5-$\sigma$ sensitivities of SIRTF bands are about 2 $\mu$Jy level at 5.8 and 8 microns and about 1 $\mu$Jy at 3.6 and 4.5 microns (open triangles). Note that similar performance is expected for Astro-F. Therefore, we will be able to distinguish the two possibilities with SIRTF or ASTRO-F observations at 3-8 micron.

At shorter wavelengths, the SED of $z \sim 12.5$ starforming galaxy sharply drops to zero below $\lambda \sim 1.7$ micron, while 53W002-HERO1 would have the flux value of 0.1 $\mu$Jy in $J$ if it is an intrinsically red object at $z \sim 2.4$. A very deep NIR observation in $J$ will reach the limit, although such observation is costly in observing time (e.g., $\sim$16 hrs for 5$\sigma$ detection with an 8-m class telescope).

In order to distinguish between "old" vs "dusty" in case that 53W002-HERO1 is at $z \sim 2$, one needs to observe 53W002-HERO1 at even longer wavelengths. The SCUBA (open diamond) and VLA (stars) sensitivities are close, but maybe only marginal for distinguishing between "old" vs "dusty", and so is the 24 micron SIRTF observation.

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## References

Bershady, M., Lowenthal, J., & Koo, D. C. 1998, 505, 50
Blain, A. W., Ivison, R. J>, & Smail, L. 1998, MNRAS, 296, L29
Chary, R., & Elbaz, D. 2001, ApJ, 556, 562
Chen, H., et al. 2002, ApJ, 570, 54
Cimatti, A., et al. 2002, **??**jnlA&A, 381, L68
Daddi, E., Cimatti, A., & Renzini, A. 2000, **??**jnlA&A, 362, L45
Dey, A., et al. 1999, ApJ, 519, 610
Dickinson, M., et al. 2000, ApJ, 531, 624
Djorgovski, S. G., Castro, S., Stern, D., & Mahabal, A. A. 2001, **??**jnlApJ, 560, L5
Elston, R., Rieke, M. J., & Rieke, G. H. 1988, 331, L77
Fan, X., et al. 2001, AJ, 122, 2833
Graham, J. R., & Dey, A. 1996, ApJ, 471, 720

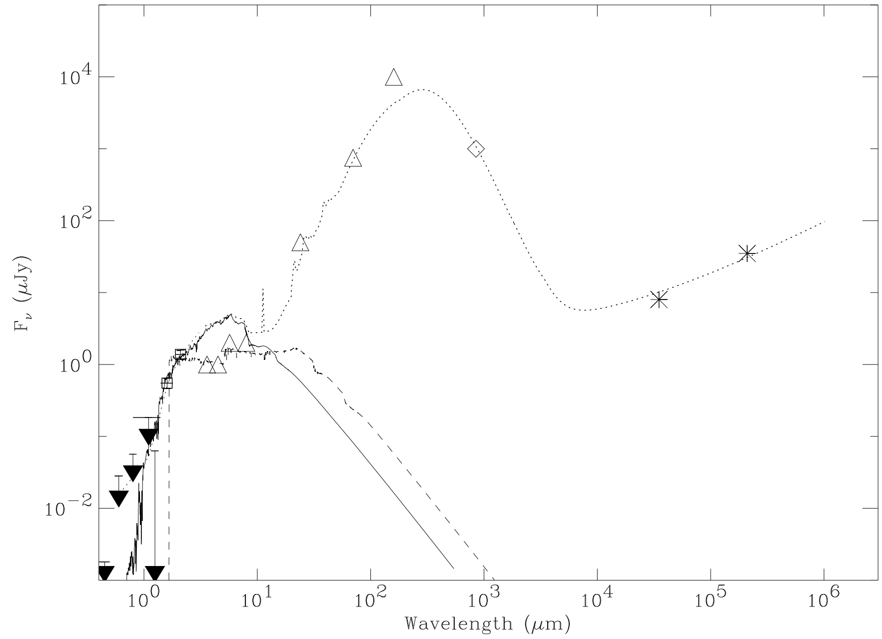


Fig. 1.3. Similar to Figure 2, now with the model lines extended to 21 cm. Also plotted are SIRTF (open triangles), SCUBA (diamond), and VLA (stars) sensitivities. SIRTF IRAC observation will be able to provide a good indication as to if 53W002-HERO1 is starforming Lyman break galaxy or not. If 53W002-HERO1 is an object at $z \sim 2$, SIRTF 24 micron, as well as submm and radio observations might tell us if 53W002-HERO1 is dusty or not.

Hall, P. B., et al. 2001, AJ, 121, 1840
Hu, E. M., & Ridgeway,S. E. 1994, AJ, 107, 1303
Im, M., et al. 2002, ApJ, 571, 136
Im, M., et al. 2001, AJ, 122, 750
Keel, W. C., Wu, W., Waddington, I., Windhorst, R. A., Pascarelle, S. M. 2002, AJ, 123, 3041
McCarthy, P. J., et al. 2001, **??**jnlApJ, 560, L131
Motohara, K., et al. 2002, **??**jnlPASJ, 54, 315
Pascarelle, S. M., Windhorst, R. A., Driver, S. P., Ostrander, E. J., & Keel, W. C. 1998, ApJ, 456, L21
Richards, E. A., et al. 1998, AJ, 116, 1039
Roche, N. D., Alamani, O., Dunlop, J., Ivison, R. J., & Willott, C. J. 2002, MNRAS, in press
Simard, L., et al. 2002, ApJ, in press
Smail, I., et al. 1999, MNRAS, 308, 1061
Smith, G. P., et al. 2002, MNRAS, 330, 1
Soifer, T., et al. 1994, ApJ, 420, L1
Thompson, D., et al. 1999, 199, 523, 100
Totani, T., Yoshii, Y., Iwamuro, F., Maihara, T., & Motohara, K. 2001, **??**jnlApJ, 588, L87
Väisänen, P., Tolestrup, E. V., & Fazio, G. G. 2001, MNRAS, 325,1241
Windhorst, R. A., Keel, W. C., & Pascarelle, S. M. 1998, ApJ494, L27
Xu, C., Londsdale, C. J., Shupe, D. L., O'linger, J., & Masci, F. 2001, ApJ, 562, 179
Yamada, T., et al. 2001, **??**jnlPASJ, 53, 1119
Yan, L., et al. 2000, AJ, 120, 575