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HERO (Hyper Extremely Red Object) in the Field near 53W002

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ABSTRACT

HERO's (Hyper Extremely Red Objects) are objects which are very red in NIR colors ($J-K \gtrsim 3$ mag). 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 HERO1, 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 ($J - K > 4.45$ mag, 2-σ). Its spectral energy distribution is consistent with that of a dusty starforming or an old galaxy at $z \simeq 2.4$, which suggests that HERO1 may be 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 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 $z \gtrsim 10$.

Subject headings: cosmology: observations — cosmology: early universe — galaxies: evolution — galaxies: formation — galaxies: high-redshift

1. Introduction

Extremely Red Objects (ERO's) 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 $R - K > 5$ mag corresponds

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to the color of passively evolving early-type galaxies at $z \gtrsim 1$ in observed frame. Studies have shown that most ERO's 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). Hyper-Extremely Red Objects (HERO's) are the reddest objects among ERO's, with very red NIR colors (Totani et al. 2001). While the majority of ERO's have a NIR color of $J - K \lesssim 2$ mag, HERO's 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 that HERO's are rare and have extreme colors, only a handful of HERO's have been discovered so far (Bershady et al, Lowenthal, & Koo 1998; Dickinson et al. 1999; Totani et al. 2001; Moahn et al. 2002; Hall et al. 2001).

Spectroscopic observations reveal that ERO's with $J - K \sim 2.5$ mag are dusty or old systems at $z \sim 1.5$ (Soifer et al. 1999; Dey et al. 1999; Cimatti et al. 1998; Liu et al. 2000). Such objects at higher redshift can have $J - K > 3$ mag, and it has been suggested that HERO's are dusty starforming objects at $z \gtrsim 2$, or old galaxies at $z \sim 2 - 3$ with their Balmer break redshifted out of J-band (e.g., Totani et al. 2001; Bershady et al.1998). Alternatively, HERO's could be Lyman break galaxies at $z \gtrsim 10$ (e.g., Dickinson et al. 1999).

In this Letter, we report the discovery of a HERO — which we name as HERO1 — 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/group of galaxies at $z \sim 2.4$ in the 53W002 field (e.g., Pascarelle et al. 1996). Our discovery marks the first detection of a HERO in the field of a $z > 2$ cluster of galaxies, which may help understand the nature of HERO's.

2. Data

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. 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 σ 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 (Williams et al. 1998). The WFPC2 data are used to place limits on the spectral energy distribution (SED) of the object in the optical. The WFPC2 data, calibrated and stacked, are retrieved from the Canadian Astronomical Data Center.

Figure 1 shows postage stamp images of 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 HERO1 is visible only in H and K' bands. FWHM of HERO1 is 0.″5 while that of stars in the NICMOS image containing 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 ± 0.″2 for 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, HERO1 is not a point source like exotic stars.

Table 1 summarizes the photometry of HERO1. Aperture magnitudes were measured using the IRAF [5] task "phot" under the DAOPHOT package, as well as "aper" task in IDL. We adopted an aperture diameter of 1.″0, which appears to maximize the S/N in K'-band. The object center in K' was used for deriving aperture magnitudes in other bands. For the K' photometry, we also provide the "best" magnitude measured using SExtractor (Bertin & Arnouts 1996). Each flux value is presented with 1-σ errors. When the significance of photometric measurements falls below ∼2-σ, we also provide 2-σ upper limit which was calculated as the measured flux plus twice of the σ value.

3. Discussion

Figure 2 shows the SED of HERO1 (points and arrows). The observed SED is compared with SED's of the following three objects: (1) solid line – a 3.0 Gyr old passively evolving galaxy at $z = 2.39$, created using the 1996 version of the Bruzual and Charlot model (1993). We assume for the SED, 0.1 Gyr burst with formation redshift, $z_{form} \simeq 10$, the Salpeter IMF, 2.5 times solar metallicity, and the cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$ and $H_0 = 65$ km/sec/Mpc; (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

[5] IRAF is distributed by the National Optical Astronomy Observatories, under contract to A.U.R.A. Inc.

extinction, but with intergalactic extinction due to neutral hydrogen. The observed broad-band SED of HERO1 is consistent with all the above reference SED's, although the J-band data may fall below the model lines of (1) and (2).

If 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; Becker et al. 2001; Djorgovki et al. 2001). Therefore, the stars in HERO1 could be typical of the sources that reionized the universe. We checked how robust the constraint on the formation redshift is, by changing the model assumptions on the metallicity, the age, and the cosmology. Although the preferred redshift of the object changes with the input values, we find that the possible formation redshift remains to be $z \gtrsim 10$.

From the SED, we estimate that the stellar mass of the HERO is $\sim 10^9\ M_\odot$, or the total mass of $10^{11}\ M_\odot$ assuming that stellar mass is one percent of the total halo mass. The prediction from theory is that the number density of $10^{11} M_\odot$ halos is only about 10^{-5} Mpc^{-3} at $z \sim 10$, while more typical halo mass is of order of $10^8 M_\odot$ (e.g, Barkana & Loeb 2001). — HERO1 may be one of the heaviest objects which formed at $z \sim 10$ or a merger product of the less massive reionizing sources.

HERO1 is located about 30″ away from 53W002 and within the field covered by the Lyman-α emitters at $z \sim 2.4$ (Pascarelle et al. 1996). If HERO1 is associated with the $z = 2.4$ proto-cluster of galaxies, one would naively expect that the 53W002 field contains more HERO's 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 □′. Nevertheless, we can compare the surface number density of HERO in 53W002 with that in other fields, to see if there is any drastic difference. At $K < 22$ mag, Motohara et al. (2002) and Totani et al. (2001) find one HERO within 4 □′ FOV from the Subaru Deep Field. Similarly, Dickinson et al. (2000) find one HERO within the Hubble Deep Field (5 □′). Bershady et al. (1998) find one object with $J - K > 3.5$ mag and a few more with $J - K > 3.0$ mag within 1.5 □′ FOV of DEEP Keck NIR images (1-σ limit). These numbers average out to the HERO surface number density of about a few tenths per □′, which is consistent with the HERO surface number density in the 53W002 field (∼1 over 4 □′). HERO1 might have nothing to do with the high-z cluster, or other fields may also contain high-z clusters. More data are clearly needed to establish any connection between HERO's and high redshift cluster of galaxies.

The field surrounding 53W002 also contains other kinds of ERO's. There are B-band dropout objects in the field, and photometric redshifts of these ERO's indicate that they are at $z \sim 1$ (Im et al. 2002, in preparation; Colbert et al. 2001). Their $J - K$ and $I - K$

colors are about 2.0 mag, and 4.0 mag, so they are bluer than HERO1. Thus, HERO1 does not appear to be associated with this possible group of red galaxies at $z \sim 1$, unless HERO1 is a rather unusual dusty galaxy at $z \sim 1$. One of the ERO's is quite faint in J-band (5-σ detection). Although this object may turn out to be a HERO, we do not classify it as a HERO since the possible J-band detection implies $J - K \gtrsim 2.4$ mag, not red enough to be classified as an HERO. HERO1 stands out among ERO's in the 53W002 as the object with the reddest $J - K$ color.

4. Future Prospects

In Figure 3, we show the SED of HERO1 with the reference lines extending to the longer wavelength. The redshifted line of HR10 is extended to the longer wavelength 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-σ 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; Dickinson & Giavalisco 2002). The SCUBA limits come 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 μJy at 3-8 micron, while intrinsically red objects at $z \sim 2$ will have a SED which steeply rises toward longer wavelength above a few μJy. The 5-σ sensitivities of SIRTF bands are about 2 μJy level at 5.8 and 8 microns and about 1 μJy at 3.6 and 4.5 microns (open triangles). Note that similar performance is expected for Astro-F (e.g., Onaka et al. 2000). Therefore, we will be able to distinguish the two possibilities with SIRTF or ASTRO-F observations at 3-8 micron.

At the shorter wavelength, the SED of $z \sim 12.5$ starforming galaxy sharply drops to zero below $\lambda \sim 1.7$ micron, while HERO1 would have the flux value of 0.1 μJy 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 5σ detection of HERO1 with an 8-m class telescope).

In order to distinguish between "old" vs "dusty" in case that HERO1 is at $z \sim 2$, one needs to observe HERO1 in even longer wavelength. 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. At 70 and 160 microns, it will be even harder to do a reliable flux extraction due to the confusion problems.

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Table 1. Photometry of HERO1

	HERO1
RA(J2000)	17:14:11.91
DEC(J2000)	50:15:41.82
B_{450}	> 30.9 (2-σ) mag
(0.46 μm)	< 0.002 (-0.012 ± 0.007) μJy
V_{606}	> 27.7 ($28.5^{+0.9}_{-0.5}$) mag
(0.60 μm)	< 0.028 (0.013 ± 0.007) μJy
I_{814}	> 26.6 ($27.3^{+0.6}_{-0.4}$) mag
(0.80 μm)	< 0.056 (0.030 ± 0.013) μJy
J_{110}	> 24.9 ($25.6^{+0.6}_{-0.4}$) mag
(1.10 μm)	< 0.183 (0.097 ± 0.043) μJy
J	> 26.1 (2-σ) mag
(1.25 μm)	< 0.063 (-0.129 ± 0.096) μJy
H_{160}	$23.12^{+0.09}_{-0.09}$ mag
(1.59 μm)	0.551 ± 0.045 μJy
K'	$21.65^{+0.08}_{-0.07}$ mag
(2.13 μm)	1.38 ± 0.09 μJy
K'_{best}	$21.51^{+0.11}_{-0.10}$ mag
(2.13 μm)	1.56 ± 0.14 μJy

Note. — Magnitudes are in Vega system; Upper limits are given as 2-σ.

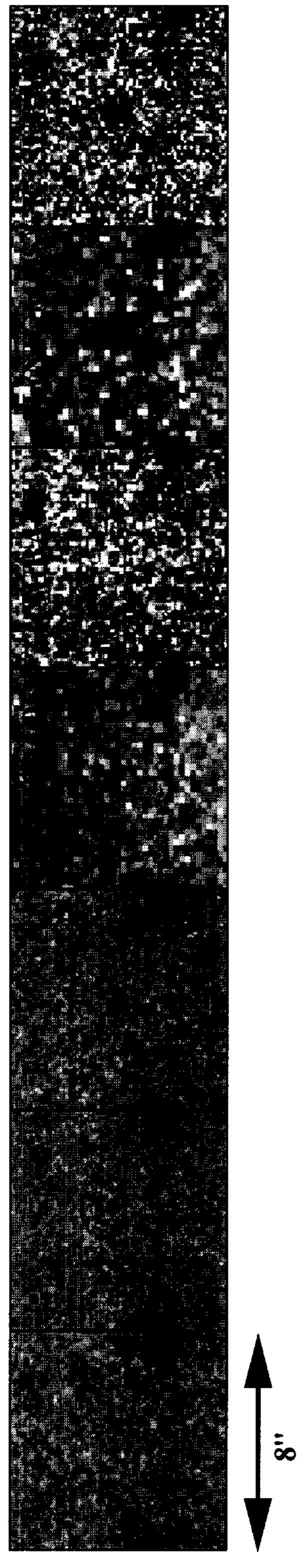

Fig. 1.— Postage stamp images of HERO1 in B, V, I, J (HST), J (Subaru), H (HST), and K' (Subaru). North is up and east to the left. Each side of the image is 8.″0 long. The object is visible in H and K' images, but is not detected in J and bluer passbands.

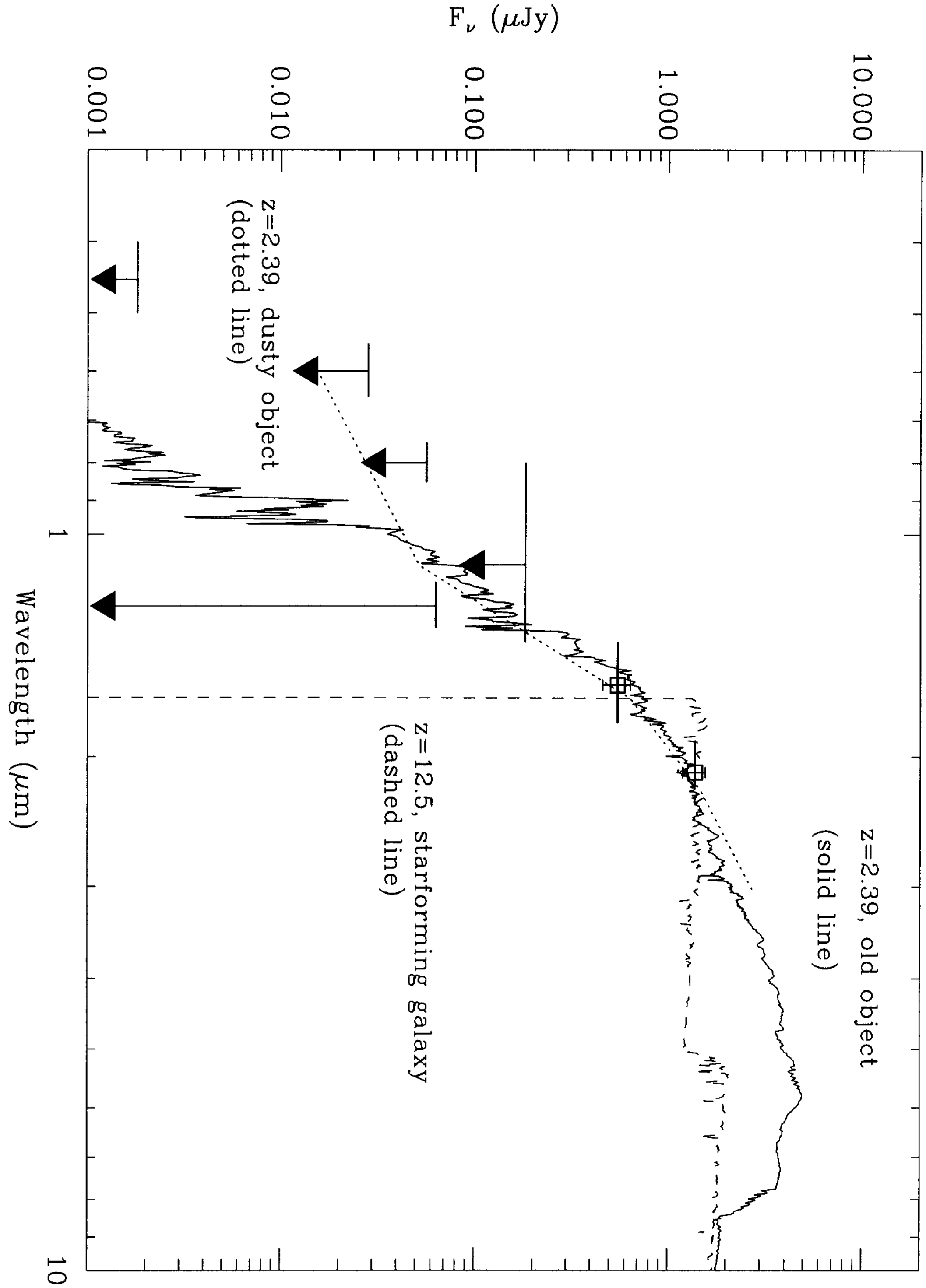

Fig. 2.— The observed SED of HERO1, compared with three reference SED's (solid line: old galaxy at $z = 2.39$, dotted line: dusty galaxy at $z = 2.39$, and dashed line: Lyman break galaxy at $z = 12.5$). The observed SED is consistent with all the reference SED's plotted.

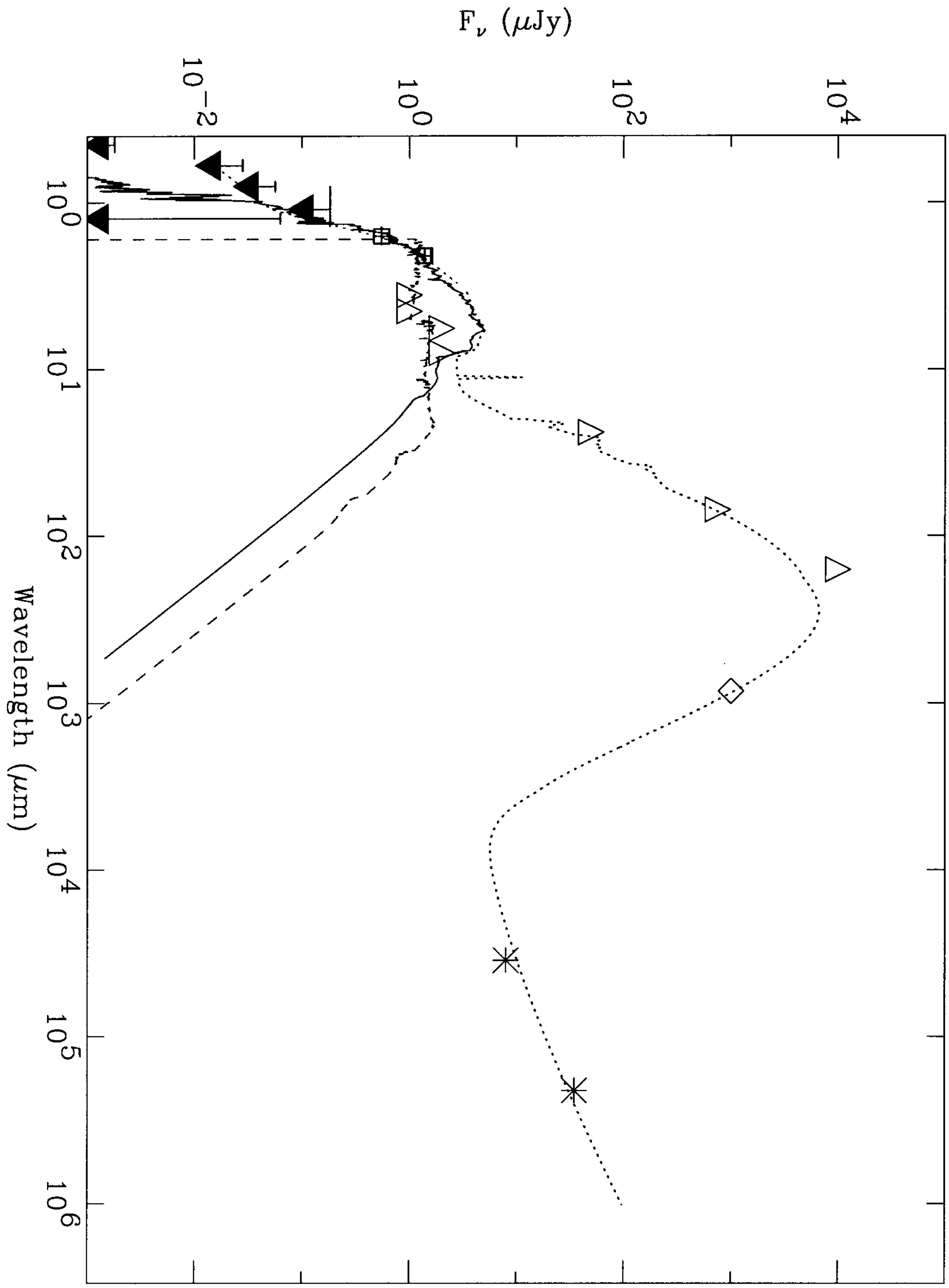

Fig. 3.— Similar to Figure 2, now with the model lines extended to 21 cm. Also plotted are SIRTF (open triangles), SCUBA (diamond), and VLA (stars) sensitivities. SIRTF IRAC observation will be able to provide a good indication as to if HERO1 is starforming Lyman break galaxy or not. If HERO1 is an object at $z \sim 2$, SIRTF 24 micron, as well as submm and radio observations might tell us if HERO1 is dusty or not.