

The Fraction of High Redshift Galaxies in Deep Infrared Selected Field Galaxy Samples

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Abstract

Recent results on the incidence of red galaxies in a > 100 square arcminute field galaxy survey to $K = 20$ and a $K = 22$ survey of the Hubble Deep Field are presented. We argue that a simple photometric redshift indicator, based on $J-K$ color and supported by spectroscopic results obtained with Keck, gives a reliable lower limit of $\sim 25\%$ for the fraction of $z > 1$ galaxies in the 100 square arcminute survey. This fraction is substantially higher than found in previous smaller samples, and is at least as consistent with predictions for pure luminosity evolution as with those for hierarchical models. The same technique yields a very low fraction for the HDF, which appears to be unusually underabundant in red galaxies.

1 Introduction

Near-infrared luminosity provides a good measure of a galaxy's mass, over a wide range of Hubble types [8], redshifts, and star formation histories [3],[11]. With the availability of sensitive, large-format infrared array cameras on large telescopes, it is now practical to obtain infrared galaxy samples reaching below L^* at $z > 1$ over areas large enough to encompass hundreds of such galaxies. In late 2001, the Space Infrared Telescope Facility (SIRTF [6]) will provide μJy -level sensitivity in the mid-infrared, enabling rest-frame $2 \mu\text{m}$ -selected samples reaching L^* at $z > 3$ to be obtained [7].

Kauffmann & Charlot[11] have recently proposed that the fraction of $z > 1$ galaxies in deep infrared K -selected samples provides a powerful means of discriminating between pure luminosity evolution (PLE) and hierarchical (CDM) scenarios for massive galaxy formation and evolution. They argue that the paucity of $z > 1$ galaxies in the Hawaii K -band samples [14], [4] already provides strong evidence against the PLE scenario and is consistent with $\Omega = 1$ CDM models. Similar arguments have been made based on the absence of red objects in surveys covering several square arcminutes to $K \sim 22$ [15], primarily the KPNO 4m Infrared Imager observations of the Hubble Deep Field (HDF IRIM) obtained by Dickinson et al.

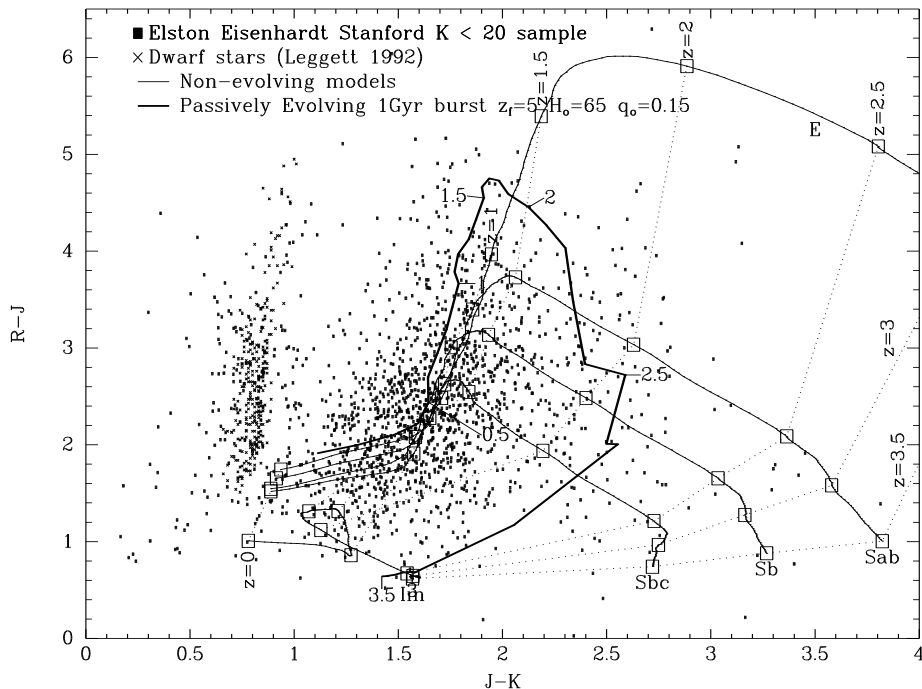


Figure 1: The $R - J$, $J - K$ color-color diagram for the EES survey. Overlaid on the data are the tracks of SEDs associated with zero redshift galaxies of the indicated types. Iso-redshift contours are plotted at redshift intervals of 0.5 from redshifts of 0 to 3.5. Also plotted on the figure are the observed RJK colors of dwarf stars from Leggett (1992).

The HDF spans a volume small enough that it would be expected to contain only a few dozen L^* galaxies with $1 < z < 2$ [5]. In combination with the strong clustering seen in Lyman break galaxies over substantially larger fields [1], this suggests that global conclusions drawn from samples like the HDF should be treated with some caution.

Using the KPNO 4m, Elston, Eisenhardt, and Stanford (hereafter EES) have recently completed a substantially larger K -selected survey, whose properties are summarized and compared to the Hawaii and HDF IRIM surveys in Table 1. The EES survey is divided into 4 regions around the sky, providing some indication of field-to-field variations caused by clustering. Figure 1 shows a color-color diagram for the survey.

Table 1. IR Field Survey Characteristics.

Survey	Bands	$K(10\sigma)$ mag	Area sq arcmin	N_{gal}	N/A #/sq arcmin
Hawaii[4]	B, I, K	19.3	26	122	5
EES	B, R, I, Z, J, K	20	124	1683	14
		19		720	6
HDF-IRIM	J, H, K	21.2	7	149	21
		20		76	11
		19		44	6

2 Extremely Red Objects

The surface density of "extremely red objects" (ERO's) in the EES sample is of interest. Graham & Dey [9] and Cimatti [2] define ERO's as objects with $R - K > 6$ and show that at

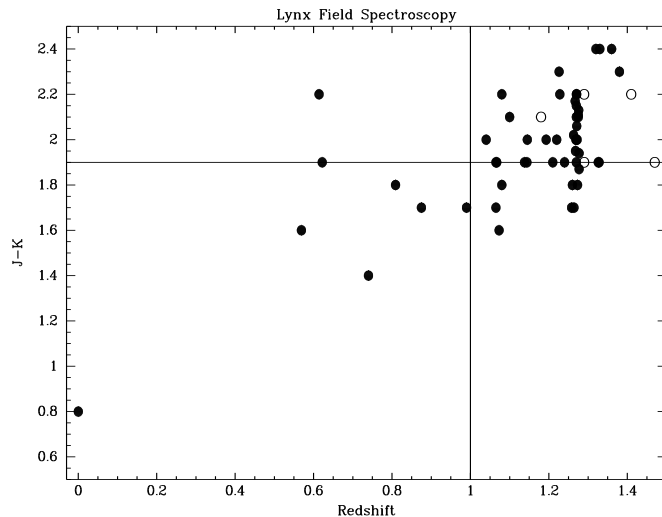


Figure 2: $J - K$ vs. redshift for the objects in the Lynx portion of the EES survey for which we have obtained slit mask spectra using the LRIS at Keck.

least one such source (Hu & Ridgway 10) is a dusty galaxy at $z = 1.44$ with detectable submm emission, implying $L_{bol} > 10^{12} L_{\odot}$ and a star formation rate of several hundred M_{\odot} per year. If the recently identified population of field sources with a surface density ~ 1 per square arcmin at comparable sub-mm fluxes [10] are similar in nature, they would dominate the global star formation rate. SIRTf will be able to characterize this population from 3.6 to 160 μm with relative ease.

We find 0.7 sources per square arcminute with $R - K > 6$ and $K < 20$. At this meeting, Barger defined very red galaxies by $I - K > 4$, finding 16 such objects to $K = 20.1$ in a 62 square arcmin survey centered on the HDF (i.e. 0.26 per square arcmin). We find an average of 2.5 sources per square arcmin (ranging from 2.1 to 3.4 among the four EES regions) with $I - K > 4$ and $K < 20$. The reason for this discrepancy is uncertain, but we suspect that at least part of the answer is that the HDF simply has an unusually low abundance of red galaxies.

3 $J - K$ as a Lower Limit to the $z > 1$ fraction

Next we consider a different measure of the red population: $J - K > 1.9$. Figure 1 shows that $J - K$ is primarily sensitive to redshift, at least for earlier type galaxies. A galaxy with the spectral energy distribution of a present day elliptical galaxy would have $J - K \approx 1.9$ at $z = 1$. Passive or active evolution will tend to make colors bluer, so the fraction of galaxies with $J - K > 1.9$ is a reasonably reliable lower limit to the fraction of galaxies with $z > 1$. Figure 2 demonstrates that this assertion holds up under spectroscopic scrutiny: while there are indeed galaxies with $J - K < 1.9$ and $z > 1$, only one object has $J - K > 1.9$ and $z < 1$.

In Table 2 we list the lower limit to the fraction of galaxies with $z > 1$ calculated from the $J - K > 1.9$ criterion for the EES and HDF IRIM samples, together with lower and upper limits determined from spectroscopy of the Hawaii and HDF IRIM samples, and predictions from Kauffmann and Charlot [11]. The spectroscopic lower limits assume that none of the objects in the sample with unknown redshifts lie at $z > 1$, while the upper limits assume that all unknown redshifts are at $z > 1$.

While the lower limits from the $J - K$ method for the EES sample are not as high as the fractions predicted for the PLE scenario [11], they are consistent with PLE, and not particularly supportive of the hierarchical model predictions. Thus we consider the PLE scenario still viable,

at least based on the probable redshift distribution of faint K -selected galaxy samples. We have obtained hundreds more spectra for the EES sample with LRIS and Keck in the fall of 1998, so we expect to determine the redshift distribution of the sample with higher confidence in the near future. We also look forward to repeating the test using SIRTf to obtain a rest-frame K -selected sample out to $z \sim 3$.

Table 2. Fraction of $z > 1$ Galaxies in IR Field Samples.

K (mag)	K&C 98		Hawaii Spec	EES $J - K > 1.9$	HDF IRIM	
	PLE	Hier			Spec	$J - K > 1.9$
16–18	28%	0%	2–11%	> 15%	14%	> 0%
18–19	54%	3%	10–17%	> 23%	5–50%	> 5%
19–20	}75%	}20%		> 28%	15–52%	> 9%
20–21			17–70%	> 3%		
21–21.5					12–88%	> 17%

4 How Representative is the HDF?

The lower limit to the fraction of K -selected $z > 1$ galaxies in the HDF determined via the $J - K > 1.9$ criterion is very low, and reasonably consistent with the hierarchical model predictions of [11] (although the spectroscopically determined limits for this fraction are much less conclusive.) Red objects appear to be uncommon in and around the HDF - a fact used by Zepf [15] and Barger to argue against a significant population of passively evolving elliptical galaxies at high redshift. This may be due to clustering effects, since early type galaxies are strongly clustered at the present epoch.

We have examined the variation in surface density of $J - K > 1.9$ and $K < 20$ objects within the EES survey. Although the mean surface density for the EES sample is 3.4 such objects per square arcmin, this value ranges from 1.0 to 6.7 in 16 EES subfields the size of the HDF. The value in the HDF itself is 0.6, reinforcing the impression that the red population HDF is unusually sparse. Results from the HDF-South should help settle this question. The total surface density of the HDF for all colors for $K < 20$ is also low, but within the EES range: 11.8 per square arcmin, whereas the EES subfields range from 11.8 (two subfields) to 25.8. This latter field contains a $z=0.58$ Rosat cluster, and the next highest density is 16.9.

The alert reader may have noticed the clump of $z = 1.27$ redshifts in Figure 2. This cluster in the Lynx EES field was identified by Stanford et al [13]. Thus it is fair to ask how representative is the EES sample, or at least the Lynx portion of it (which also includes the $z = 0.58$ cluster)? The surface density of $J - K > 1.9$, $K < 20$ objects in Lynx is 3.6 per square arcmin, and 16 per square arcmin for all $J - K$, vs. 3.4 and 13.5 for these values respectively for the entire EES sample. The EES sample comoving volume out to $z \sim 2$ is a few 10^5 Mpc³. If the present number density of clusters ($\sim 10^{-5}$ Mpc⁻³) does not evolve rapidly, the presence of these clusters is not surprising.

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