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AEGIS: The Diversity of Bright Near-IR Selected Distant Red Galaxies

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ABSTRACT

We use deep and wide near infrared (NIR) imaging from the Palomar telescope combined with DEEP2 spectroscopy and Hubble Space Telescope (HST) and Chandra Space Telescope imaging to investigate the nature of galaxies that are red in NIR colors. We locate these 'distant red galaxies' (DRGs) through the color cut $(J - K)_{\rm vega} > 2.3$ over 0.7 deg^2, where we find 1010 DRG candidates down to $K_{\rm s} = 20.5$. We combine 95 high quality spectroscopic redshifts with photometric redshifts from BRIJK photometry to determine the redshift and stellar mass distributions for these systems, and morphological/structural and X-ray properties for 107 DRGs in the Extended Groth Strip. We find that many bright $(J - K)_{\rm vega} > 2.3$ galaxies with $K_{\rm s} < 20.5$ are at redshifts $z < 2$, with 64% between $1 < z < 2$. The stellar mass distributions for these galaxies is broad, ranging from $10^9 - 10^{12}$ M$_\odot$, but with most $z > 2$ systems massive with M$_* > 10^{11}$ M$_\odot$. HST imaging shows that the structural properties and morphologies of DRGs are also diverse, with the majority elliptical/compact

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(57%), and the remainder edge-on spirals (7%), and peculiar galaxies (29%). The DRGs at $z < 1.4$ with high quality spectroscopic redshifts are generally compact, with small half-light radii, and span a range in rest-frame optical properties. The spectral energy distributions for these objects differ from higher redshift DRGs: they are bluer by one magnitude in observed $(I - J)$ color. A pure IR color selection of high redshift populations is not sufficient to identify unique populations, and other colors, or spectroscopic redshifts are needed to produce homogeneous samples.

1. Introduction

Uncovering the formation mechanisms of the most massive galaxies has a long history and has largely driven the field of galaxy formation and evolution. Traditional analyses of stellar populations in nearby ellipticals reveal that the bulk of the stars in the most massive galaxies formed early, within a few Gyr of the Big Bang (e.g., Trager et al. 2000). Observing distant galaxies is complementary to nearby galaxy age-dating, as it allows us to directly observe galaxies while they are forming. Early detections of high redshift galaxies revealed that UV bright star forming galaxies at $z \sim 3$ are dominated by relatively low stellar mass systems ($\sim 10^{10}$ M$_\odot$) (Papovich et al. 2005). As the most massive galaxies today are $> 10^{11.5}$ M$_\odot$, this implies that high$-z$ galaxies grow by a factor of 5-10 through some process, such as merging (e.g., Conselice et al. 2003; Conselice 2006).

It seems likely that at least some progenitors of today's massive galaxies are not bright in the UV, and a population of near infrared (NIR) selected 'Distant Red Galaxies' (DRGs) was described by Saracco et al. (2001) and Franx et al. (2003), who suggested that some of these systems are the progenitors of the most massive present day galaxies. These DRGs are selected using a single color cut, $(J - K)_{\mathrm{vega}} > 2.3$, and thus require near infrared (NIR) imaging to detect. While it has been proposed that DRGs are massive $z > 2$ galaxies, the bright end of this population has yet to be studied, and thus we do not yet know the general characteristics of red galaxies selected in the near infrared.

We investigate this problem by examining the redshifts, masses, morphologies and spectra of DRGs in the Extended Groth Strip (EGS). We study 1010 bright DRGs with $K_{\mathrm{s}} < 20.5$ within the EGS, and two other fields that are part of our NIR survey with the Palomar telescope. We examine the structures and morphologies of DRGs that are coincident between the ACS imaging in the EGS and our NIR survey. We find that a high fraction of DRGs at $K_{\mathrm{s}} < 20.5$ are at $z < 2$, with the majority between $1 < z < 2$, including 95 (10%) with spectroscopic redshifts. We present an initial study of these NIR selected galaxies at $z < 1.4$ and

conclude that they are small, low mass, AGN/star formation dominated galaxies. Furthermore, we find a diversity in the morphological properties of DRGs at all redshifts, suggesting that there is a wide diversity of properties for galaxies selected with the $(J - K)_{\mathrm{vega}} > 2.3$ color cut, perhaps even larger than that seen for traditional EROs (Moustakas et al. 2004). In this paper we assume the following cosmology: $H_0 = 70$ km s^{-1} Mpc^{-1}, $\Omega_\lambda = 0.7$, and $\Omega_{\mathrm{m}} = 0.3$, and use Vega magnitude units throughout.

2. Data and Sample

The data used in this paper originate from multiple data sets partially associated with the All-wavelength Extended Groth Strip International Survey (AEGIS) (Davis et al. 2006). The main source of data is from the Palomar Observatory Wide-Field Infrared Survey (POWIR) (Bundy et al. 2005a,b; Conselice et al. in prep), while other sources include DEEP2 spectroscopy (Davis et al. 2003), one orbit Hubble Space Telescope (HST) imaging using the Advanced Camera for Surveys (ACS) of the EGS (Lotz et al. 2006), and an X-ray survey of the region (Nandra et al. 2006 in prep). The POWIR data were obtained from September 2002 until October 2005 at the Palomar Observatory 5 meter using the Wide-field Infrared Camera (WIRC). For the J and K data we cover a total of ~ 0.7 deg^2 to 5-σ point source sensitivities of $K_{\mathrm{s}} = 20.5 - 21.5$ and $J = 22.5 - 23$. Within the EGS, where our highest quality data exist, we image 0.2 deg^2 to a 5 sigma depth of $K_{\mathrm{s}} = 21.1$ and $J = 23$ for point sources. To construct a sample of DRGs which is nearly complete in the K-band, we limit our study of DRGs to those at $K_{\mathrm{s}} < 20.5$.

We select DRGs through the use of a $(J - K)_{\mathrm{vega}} > 2.3$ cut. To supplement the existing 95 DEEP2 spectroscopic redshifts, we calculate photometric redshifts derived from BRIJK photometry using the ANNz method for $z < 1.4$ systems, and hyper-z for those at $z > 1.4$. The photometric redshift accuracy at $z < 1.4$ for all galaxies is quite good, with $\delta z/z = 0.05$, based on comparisons to $> 10,000$ spectroscopic redshifts. The subset of 95 DRGs with $z < 1.4$ spectroscopy have a slightly softer accuracy of $\delta z/z = 0.07$, with very few catastrophic mismatches. We test our $z > 1.4$ photometric redshifts by comparing to 44 galaxies in the Steidel et al. (2004) BM/BX $1.5 < z < 2.5$ population, where we find a lower accuracy of $\delta z/z = 0.22$.

We use the spectral energy distributions (SEDs) and spectroscopic/photometric redshifts to calculate stellar masses utilizing the methods outlined in Bundy et al. (2005a,b). Our star formation histories are parameterized by a single exponentially declining star formation event. We vary the metallicity, dust extinction and age of these various models to calculate the distribution of stellar masses using a Chabrier IMF (see Bundy et al. 2005a,b

for a detailed discussion).

3. Results

3.1. Basic Redshift and Mass Characteristics

We find a total of 1010 DRGs, brighter than $K_s = 20.5$, over our 0.7 deg^2 (2520 arcmin^2) Palomar survey area, including two fields in addition to the EGS. In comparison to previous work, van Dokkum et al. (2006) studied ~ 200 DRGs over 400 arcmin^2, FIRES 14 DRGs over 100 arcmin^2, and Papovich et al. (2006) 153 DRGs over 130 arcmin^2, all with similar DRG number densities at $K_s < 20.5$ as found in our study. Out of our 1010 NIR selected DRGs, we determine that 55 are stars based on their optical colors and unresolved structures. The DRG redshift distribution is shown in Figure 1. A total of 95 of these DRGs have secure spectroscopic redshifts taken with the DEIMOS spectrograph as part of the DEEP2 survey (Davis et al. 2003). This gives us a lower limit of $\sim 10\%$ on $z < 1.4$ galaxies in pure photometrically selected DRG samples to $K_s = 20.5$. Using these redshifts with our calibrated photometric redshifts at $z < 1.4$, we find that $\sim 70\%$ of $K_s < 20.5$ DRGs are at $z < 1.4$, but most of the DRG population (64%) is between $1 < z < 2$. Objects at $z > 2$ represent $\sim 4\%$ of the $K_s < 20.5$ DRG population, while $\sim 25\%$ of the population is found between $0.5 < z < 1$. This implies that bright DRGs have a broad redshift distribution, which is also found in other recent studies (Reddy et al. 2005; Papovich et al. 2006; Grazian et al. 2006).

We plot the stellar mass distribution for our sample in Figure 1b. From this we conclude that $(J - K)_{\mathrm{vega}} > 2.3$ selected galaxies do not uniquely sample high-mass galaxies, with a low-redshift 'contamination' rate approximately similar to what Franx et al. (2003) estimate based on Smail et al. (2002). DRGs however do select high redshift systems, generally at $z > 0.8$, and have a redshift distribution broader than the ERO population (Moustakas et al. 2004). A $(J - K)_{\mathrm{vega}} > 2.3$ selection at $z \sim 1.5$ measures approximate $(B - I)$ colors similar to dusty or old galaxies at those redshifts, based on 6 Gyr single burst stellar population models. In Figure 2 we plot the $(J - K)$ vs. K_s diagram for all DRGs at $z > 1.5$ that have stellar masses $> 10^{11}$ M$_\odot$. The most massive galaxies with masses $> 10^{11.5}$ M$_\odot$ are shown as red boxes for $1.5 < z < 2.0$ systems, and blue circles for those at $z > 2$. The green crosses represent galaxies with M$_* > 10^{11}$ M$_\odot$ at $z > 2$. The average $(J - K)$ color for all galaxies at $z > 2$ with M$_* > 10^{11}$ M$_\odot$ is $< (J - K) >= 2.3 \pm 0.62$, while the most massive systems with M$_* > 10^{11.5}$ M$_\odot$ have a mean color of $< (J - K) >= 2.4 \pm 0.7$. Although the average massive galaxy has a similar color as the DRG limit, we find that a significant number ($\sim 50\%$) of all massive galaxies at $2 < z < 3$ will be missed by the standard DRG selection,

in agreement with van Dokkum et al. (2006). These results are robust when using brighter magnitude cuts where our photometry is more accurate, and at redder color limits, up to $(J - K)_{\text{vega}} > 3.3$. These trends also remain after we select only galaxies that are redder than 1 σ of the DRG limit, and after testing our selection through a bootstrap resampling. That is, the diversity in redshifts/masses for bright DRGs is not produced by photometric errors bringing up galaxies into the DRG cut.

We find however that at $z > 2$ the DRG selection limit to $K_{\text{s}} = 20.5$ does locate very massive galaxies, with an average stellar mass of $<M_*> = 10^{11.7\pm0.2}$ $M_\odot$. The average DRG at all redshifts has a stellar mass of $M_* = 10^{10.8\pm0.5}$ $M_\odot$, with the spectroscopic sample at $z < 1.4$ having an average stellar mass of $M_* = 10^{10.5\pm0.3}$ $M_\odot$. For the remainder of this paper we focus on the DRGs found within the EGS region, where we have ancillory HST and X-ray data.

3.2. Structures and Morphologies of DRGs

Due to the ACS overlap with our NIR imaging, we can determine the morphological properties of 107 DRGs at $K_{\text{s}} < 20.5$ up to $z \sim 4$. We utilize both apparent eye-ball morphologies and quantitative measurements of size and structure on the F814W ACS imaging in the EGS to determine what type of galaxies DRGs are. We classify by eye our galaxies into the types (with the number of objects in each class): ellipticals/compact (61), peculiars (31), disks (0), edge-on disks (7), and those too faint to classify (8) following the method described in Conselice et al. (2005). The morphologies for the $(J - K)_{\text{vega}} > 2.3$ galaxies show a diversity of types, as can be seen in Figure 3, similar to the situation for lower redshift EROs (Moustakas et al. 2004). The most common type are ellipticals/compact making up 57% of the total DRG sample, with most of these (80%) compact. About 7% of the sample are composed of edge-on disks, which are likely red in $(J - K)$ due to dust redenning. Peculiars account for the remainder (29%) of the DRG sample. At $z > 2$ there is roughly a similar mixture of ellilptical and peculiars. We have morphologies for 14 systems with spectroscopic redshifts, the majority of which are compact (§4). We find very little evolution in the morphological distribution with redshift, with a slight increase in the relative number of peculiar galaxies at higher redshift.

We also utilized the revised CAS system (Conselice 2003; Conselice et al. 2004) to quantify the structures of the $(J - K)_{\text{vega}} > 2.3$ galaxies. The CAS (concentration, asymmetry, clumpiness) parameters are a non-parameteric method for measuring the structures of galaxies as resolved on CCD images (Conselice 2003). As expected from the eye-ball classifications, we find a diversity of CAS values. For the systems with spectroscopic redshifts at

$z < 1.4$ we find average values, $< C >= 2.4 \pm 0.1$, $< A >= 0.26 \pm 0.11$, $< S >= 0.09 \pm 0.06$, which is typical for nearby normal galaxies, and spirals with exponential profiles (Conselice 2003). We find nearly the same values for galaxies with $z < 1.4$ photometric redshifts. For the higher redshift sample at $z > 1.5$ we find that the morphologically classified ellipticals/compacts are more concentrated with $< C >= 3.0 \pm 0.5$, with many systems at $C > 3.3$, similar in morphology to nearby massive ellipticals. Furthermore, as we are examining $z > 1.4$ systems in the UV, we are likely underestimating the rest-frame optical light concentration (Taylor et al. 2006, submitted). This is an indication, along with their high masses, that these $z > 1.5$ systems are likely elliptical progenitors.

There are two caveats to using the F814W band ACS imaging on these galaxies. The first is that there are redshift effects which will change the measured parameters (Conselice et al. 2000a,b; Conselice 2003). Systems at $z > 1.2$ are also viewed in the rest-frame ultraviolet, complicating comparisons to nearby galaxies viewed in the optical. There is evidence, however, that distant galaxies dominated by UV bright star formation look similar in the rest-frame optical and UV (Windhorst et al. 2002; Papovich et al. 2005; Conselice et al. 2005).

4. Low Redshift $z < 1.4$ DRGs

We have 95 confirmed high quality spectroscopic redshifts for DRGs at $z < 1.4$. About 7% of these systems are traditional EROs with $(R - K)_{\mathrm{vega}} > 5$, while $\sim 33\%$ have red optical/NIR colors, with $(R - K)_{\mathrm{vega}} > 4$. The average magnitude of our spectroscopically confirmed lower redshift DRGs at $z < 1.4$ is $<\mathrm{M_B}> = -20.48 \pm 1.27$, with an average color of $< (U - B) >= -0.16 \pm 0.23$, and these systems span the color-magnitude relation, suggesting a heterogeneous origin. Our lower redshift DRGs are a mangitude bluer in observed $(I - J)$ color compared to the $z > 1.5$ DRGs. They are also roughly a magnitude brighter than the DEEP2 spectroscopic limit, with an average $<\mathrm{R}> = 23.3$. The average half-light radii of the spectroscopically selected $(J - K)_{\mathrm{vega}} > 2.3$ galaxies is 0.7 ± 1 kpc, with an average stellar mass of $10^{9.8 \pm 0.46}$ $\mathrm{M_\odot}$ within the ACS region. The concentration indices of these systems are moderate, with a average of $\mathrm{C} = 2.8 \pm 0.4$, typical for low mass ellipticals, or disks (Conselice 2003). The systems at $z < 1.4$ with photometric redshifts in the ACS region have very similar masses, sizes and morphologies as the spectroscopic sample. Interestingly, none of these lower redshift DRGs are face-on disks, which is the most common galaxy type at $z < 1.4$ (Conselice et al. 2005).

To further investigate the nature of the $z < 1.4$ objects we combine the spectra of all DRGs with spectroscopy to produce a co-added non-flux weighted (Figure 4) spectrum.

This spectrum shows that the $z < 1.4$ DRGs with emission lines, host star formation, AGN activity, as well as evidence for post starbursts with ages 1 Gyr, revealed through strong Balmer absorption lines. Features produced by star formation, including [OII] and Balmer absorption lines, are seen, as well as higher excitation lines such as [NeIII] and [OIII]. The average ratio of $([OIII]\lambda5007)/(H\beta\ \lambda4861) \sim 4 - 4.5$ after correcting for $H\beta$ absorption. This suggests a mixture of star formation and AGNs (Seyfert 2s) could be responsible for the lower redshift sources (Veilleux & Osterbrock 1987). The preliminary X-ray Chandra catalog of the EGS reveals that a lower limit of six $z < 2$ DRGs have bright X-ray detections to a limit of $\sim 10^{-16}$ erg s^{-1} cm^{-2}, all with photo-zs, and soft hardness ratios. Other sources could be obscured AGN in moderate L_x systems. We conclude that $(J - K)_{\rm vega} > 2.3$ systems at $z < 1.4$ appear to have average masses, a moderate concentration of light, and are host to star formation and AGN activity, but otherwise are heterogenous.

5.   Discussion

With several large area and deep NIR surveys coming online soon, such as UKIDSS and VISTA, it is desirable to understand the properties of pure photometrically selected NIR samples, such as the DRGs with $(J - K)_{\rm vega} > 2.3$. Our results suggest that bright DRGs are a mixed population, as other smaller studies have previously found (Reddy et al. 2005; Papovich et al. 2006; van Dokkum et al. 2006). The differences between the original DRG, Franx et al. (2003), study and ours is due to the depth of the surveys, with Franx et al. being several magnitudes deeper, although most DRGs studied in detail thus far are at $K_s < 20$. Because DRGs have unique SEDs, their photometric redshifts are potentially harder to measure accurately, and these results, and others that utilize photometric redshifts, should be viewed as tentative until significant numbers of spectroscopic redshifts become available. This is demonstrated by a high absolute lower limit (10%) contribution to the entire DRG population from $z < 1.4$ galaxies, which tend to be small, lower mass galaxies with optical AGN signatures. The morphological mix derived in this paper is however robust, regardless of the redshift distribution. The DRG population is morphologically dominated by compact galaxies, with edge-on spirals and peculiars making up 36% of the population. In the future multi-object near-IR spectrographs will be necessary to make definitive progress in our understanding of non-UV bright galaxies at $z > 2$.

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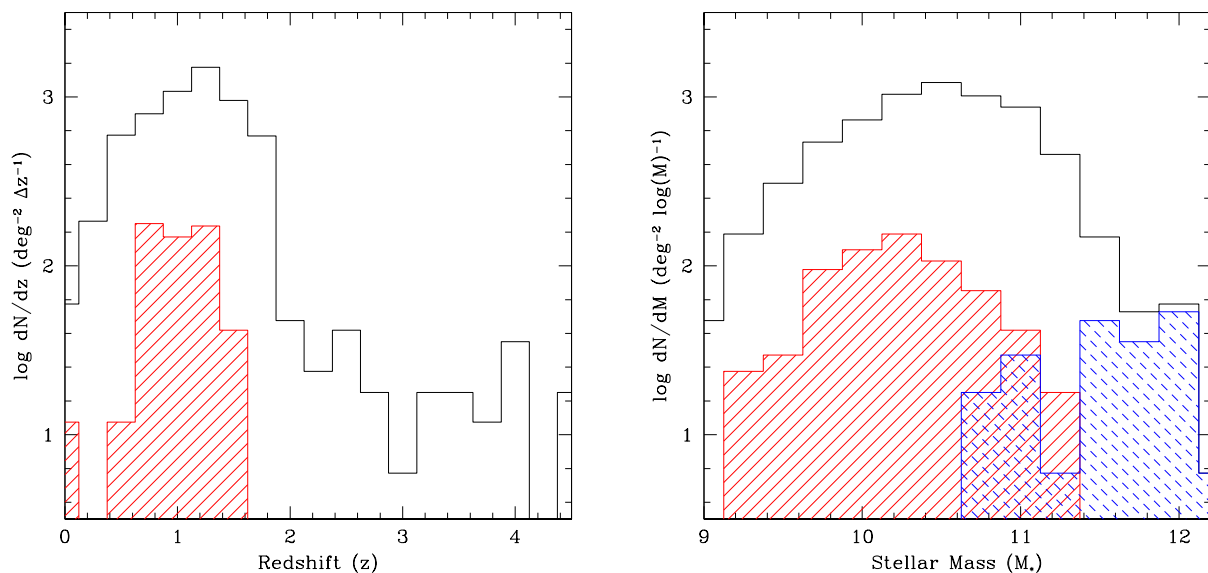
Fig. 1.— Redshift and stellar mass distributions for the $K_s < 20.5$, DRG $(J - K)_{vega} > 2.3$ population over 0.7 deg^2. The shaded red histogram in the redshift (left) panel is for galaxies with reliable spectroscopic redshifts. The solid shaded red histogram for the mass (right) panel is for galaxies with spectroscopic redshifts, while the blue dashed shaded histogram shows the stellar mass distribution for galaxies at $z > 2$.
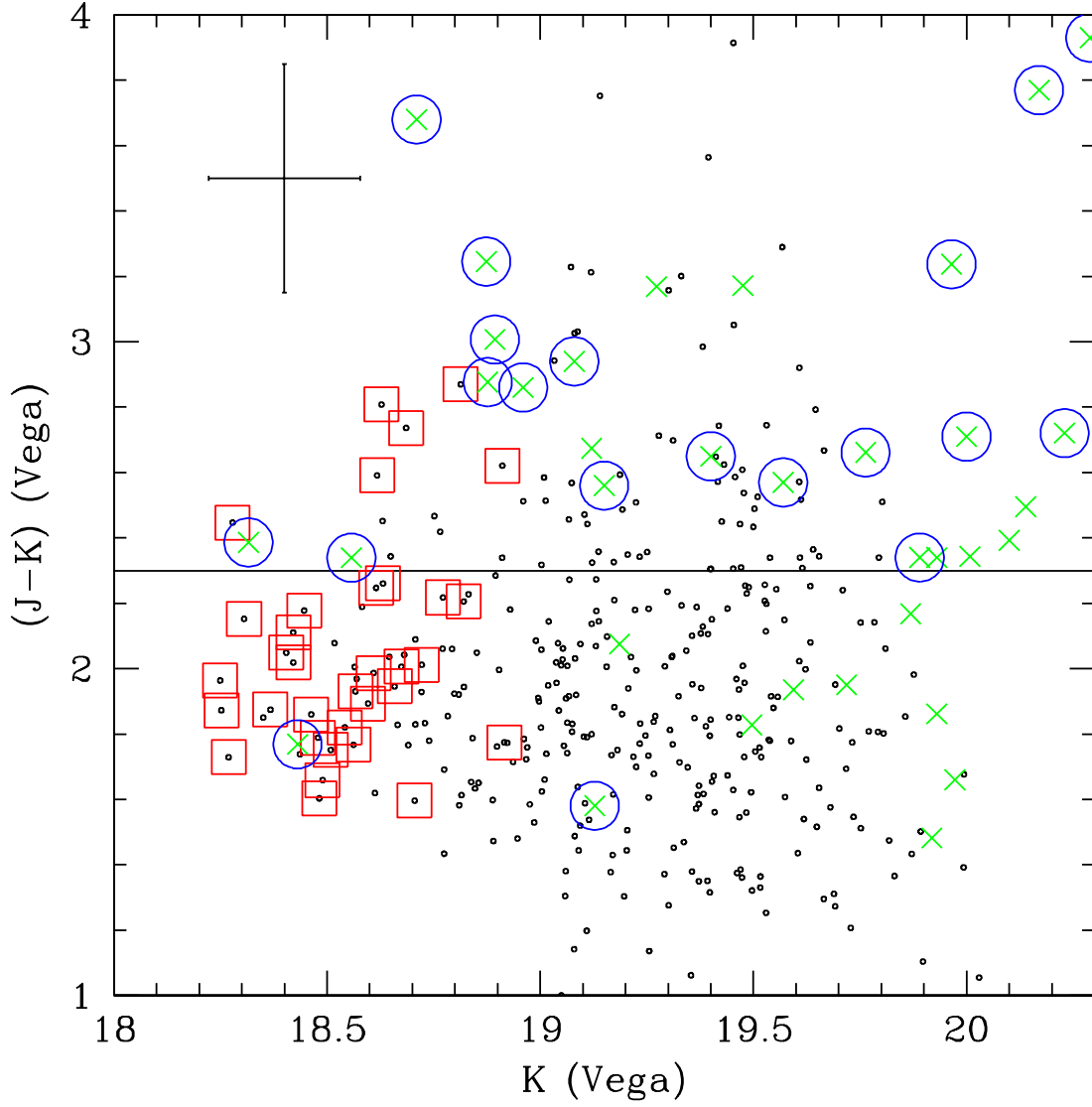
Fig. 2.— The $(J - K)_{\text{vega}}$ vs. K_s diagram for objects in the total Palomar coverage areas. Every point is for an object at $z > 1.5$ which has a measured stellar mass with $M_* > 10^{11}$ $M_\odot$. Objects surrounded by red boxes are objects with $M_* > 10^{11.5}$ $M_\odot$ at $1.5 < z < 2.0$, while circled objects are systems with $M_* > 10^{11.5}$ $M_\odot$ at $z > 2.0$. Objects at $z > 2$ and with $M_* > 10^{11}$ $M_\odot$ are plotted as green crosses. The horizontal line is the limit for DRGs. The typical error is shown in the upper left.
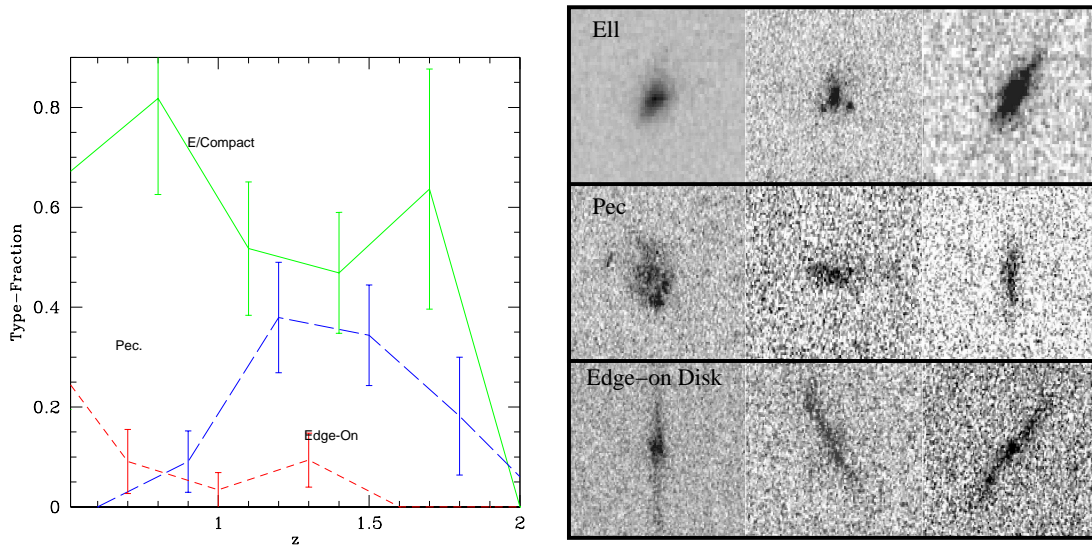
Fig. 3.— The morphological type fractions for DRGs with $K_\mathrm{s} < 20.5$ in the EGS. The fractions are displayed as: a solid green line for the compact/ellipticals, a long-dashed line for peculiars, and a short-dashed red line for edge-on disks. Examples of each morphological type are shown on the right hand side.
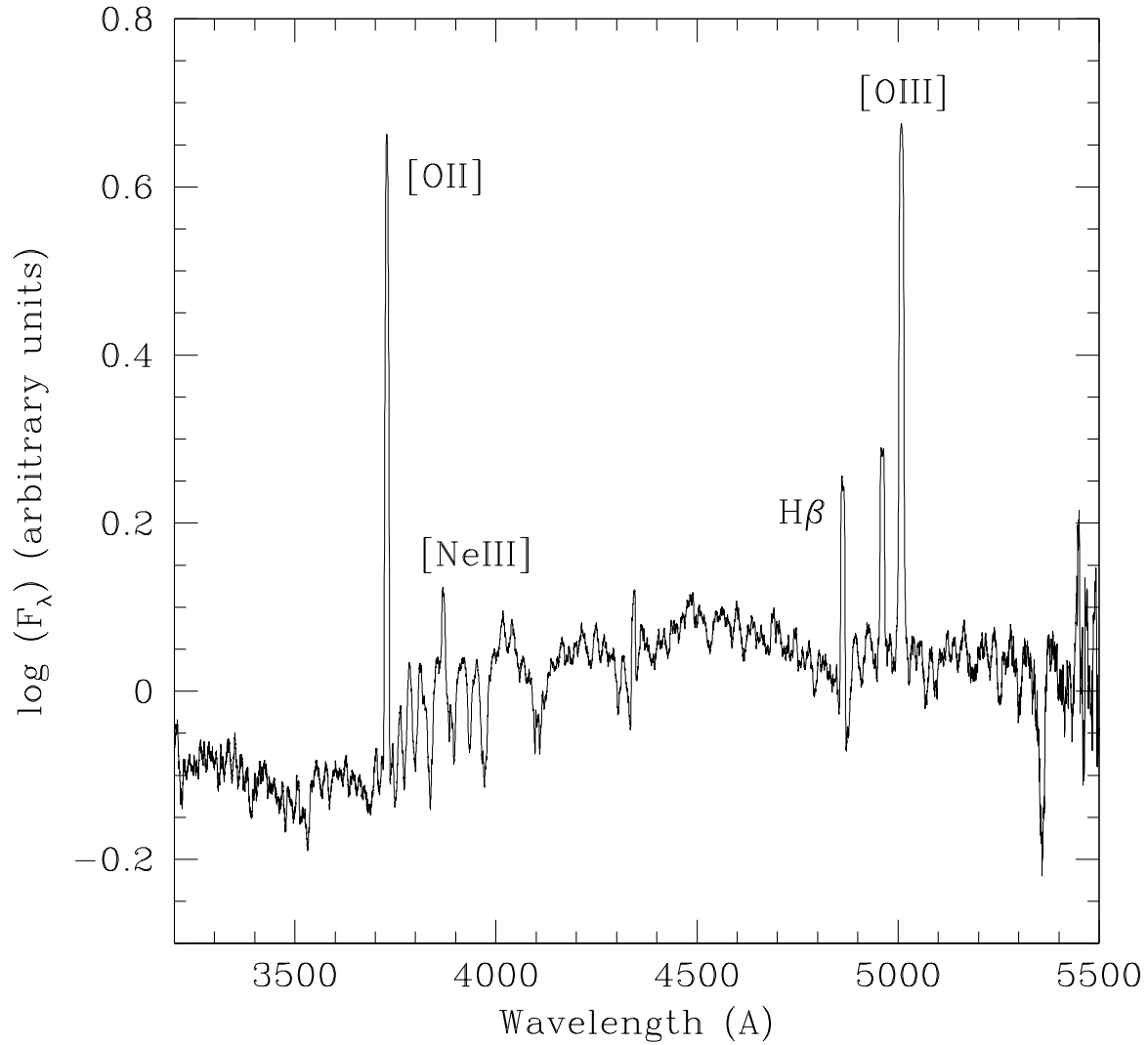
Fig. 4.— The co-added spectrum for the lower redshift DRGs with a high quality spectra from the DEEP2 survey. Lines due to star formation, such as Hβ can be seen in tandem with high ionization lines, such as [NeIII], which suggests the presence of AGN activity. The ratio of ([OIII]λ5007)/(Hβ λ4861) is also high, which is also indicative of AGN excitation for some systems.