A CENSUS OF OPTICAL AND NEAR-INFRARED SELECTED STAR-FORMING AND PASSIVELY EVOLVING GALAXIES AT REDSHIFT z ~ 21

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Received 2005 April 21; accepted 2005 July 8

ABSTRACT

Using the extensive multiwavelength data in the GOODS-North field, including our ground-based rest-frame UV spectroscopy and near-IR imaging, we construct and draw comparisons between samples of optical and near-IR selected star-forming and passively evolving galaxies at redshifts 1.4 ≤ z ≤ 2.6. We find overlap at the 70%–80% level in samples of z ~ 2 star-forming galaxies selected by their optical (U∗GR) and near-IR (BzK) colors when subjected to common K-band limits. Deep Chandra data indicate a ~25% AGN fraction among near-IR selected objects, much of which occurs among near-IR bright objects (Ks < 20; Vega). Using X-rays as a proxy for the bolometric star formation rate (SFR) and stacking the X-ray emission for the remaining (non-AGN) galaxies, we find that the SFR distributions of U∗GR, BzK, and J − Ks > 2.3 galaxies (i.e., distant red galaxies; DRGs) are very similar as a function of Ks, with Ks < 20 galaxies having SFR ~ 120 M⊙ yr−1, a factor of 2–3 higher than those with Ks > 20.5. The absence of X-ray emission from the reddest DRGs and BzK galaxies with (z − K)AB ≥ 3 indicates that they must have declining star formation histories to explain their red colors and low SFRs. While the M/L ratio of passively evolving galaxies may be larger on average, the Spitzer IRAC data indicate that their inferred stellar masses do not exceed the range spanned by optically selected galaxies, suggesting that the disparity in current SFR may not indicate a fundamental difference between optical and near-IR selected massive galaxies (M* > 1011 M⊙). We consider the contribution of optical, near-IR, and submillimeter selected galaxies to the star formation rate density (SFRD) at z ~ 2, taking into account sample overlap. The SFRD in the interval 1.4 ≤ z ≤ 2.6 of U∗GR and BzK galaxies to Ks = 22 and DRGs to Ks = 21 is ~0.10 ± 0.02 M⊙ yr−1 Mpc−3. Optically selected galaxies to R = 25.5 and Ks = 22.0 account for ~70% of this total. Greater than 80% of radio-selected submillimeter galaxies to S850 um ~ 4 mJy with redshifts 1.4 < z < 2.6 satisfy either one or more of the BX/BM, BzK, and DRG criteria.

Subject headings: cosmology: observations — galaxies: evolution — galaxies: high-redshift — galaxies: starburst — infrared: galaxies — X-rays: galaxies

Online material: color figures

1. INTRODUCTION

A number of surveys have been developed to select galaxies at z ~ 2, determine their bolometric star formation rates (SFRs), and compare with other multiwavelength studies to form a census of the total star formation rate density (SFRD) at z ~ 2 (e.g., Steidel et al. 2004; Rubin et al. 2004; Daddi et al. 2004b). A parallel line of study has been to compare optical and near-IR selected galaxies that are the plausible progenitors of the local population of passively evolving massive galaxies. However, biases inherent in surveys that select galaxies based on their star formation activity (e.g., Steidel et al. 2004) and stellar mass (e.g., Cimatti et al. 2002b; Glazebrook et al. 2004) can complicate such comparisons. Only with an accurate knowledge of the overlap between these samples can we begin to address the associations between galaxies selected in different ways, their mutual contribution to the SFRD at z ~ 2, and the prevalence and properties of passively evolving and massive galaxies at high redshift. Quantifying this overlap between optical and near-IR surveys is a primary goal of this paper.

In practice, optical surveys are designed to efficiently select galaxies with a specific range of properties. The imaging required for optical selection is generally a small fraction of the time required for near-IR imaging and can cover much larger areas within that time. In contrast, near-IR surveys sample galaxies over a wider baseline in wavelength than optical surveys and can include galaxies relevant to studying both the SFRD and stellar mass density at high redshift. However, in order to achieve a depth similar (and area comparable) to that of optical surveys, near-IR selection requires extremely deep imaging and can be quite expensive in terms of telescope time due to the relatively small size of...
IR arrays compared to CCDs. Furthermore, the “color” of the terrestrial background for imaging is \((B - K_s)_\text{AB} \approx 7\) mag, much redder than all but the most extreme \(z \sim 2\) galaxies. Once selected, of course, such extreme galaxies then require heroic efforts to obtain spectra, whereas optical selection, particularly at redshifts where key features fall shortward of the bright OH emission “forest,” virtually guarantees that one can obtain a spectroscopic redshift with a modest investment of 8–10 m telescope time and a spectrograph with reasonably high throughput. As we show below, optical and near-IR surveys complement each other in a way that is necessary for obtaining a reasonably complete census of galaxies at high redshift.

The SFRs of \(z \sim 2\) galaxies are typically estimated by employing locally calibrated relations between emission at which the galaxies can be easily detected (e.g., UV, H\(\alpha\)) and their FIR emission. The X-ray luminosity of local nonactive galaxies results primarily from high-mass X-ray binaries, supernovae, and diffuse hot gas (e.g., Grimm et al. 2002; Strickland et al. 2004); all of these sources of X-ray emission are related to the star formation activity on timescales of \(< 100\) Myr. Observations of galaxies in the local universe show a tight correlation between X-ray and FIR luminosity, prompting the use of X-ray emission as an SFR indicator (Ranalli et al. 2003). This correlation between X-ray emission and SFR applies to galaxies with a very large range in SFRs, from \(-0.1\) to \(1000 M_\odot\) yr\(^{-1}\). Stacking analyses at X-ray and radio wavelengths, and comparison with UV emission, indicate that the local SFR relations appear to give comparable estimates of the instantaneous SFRs of galaxies after assuming continuous star formation models and correcting for dust (e.g., Reddy & Steidel 2004; Nandra et al. 2002; Seibert et al. 2002).

Two surveys designed to select massive galaxies at redshifts 1.4 \(\leq z \leq 2.5\) and passively evolving (PE) galaxies at redshifts \(z \geq 2\), respectively, are the K20 and FIRES surveys. The K20 and FIRES selection criteria were developed to take advantage of the sensitivity of rest-frame optical light and color to stellar mass and the strength of the Balmer break, respectively, for \(z \sim 2\) galaxies (e.g., Cimatti et al. 2002a; Franx et al. 2003). The Gemini Deep Imaging Survey (GDDS) extends this near-IR technique to target massive galaxies at slightly lower redshifts \((0.8 \leq z \leq 2.0)\;\;\;\text{(Abraham et al. 2004)}\).

X-ray stacking analyses of the brightest galaxies in the K20 and FIRES surveys indicate an average SFR a factor of 4–5 times larger than for optically selected \(z \sim 2\) galaxies (Daddi et al. 2004a; Rubin et al. 2004), inviting the conclusion that optical selection misses a large fraction of the star formation density at high redshift. While it is certainly true that optical surveys miss some fraction of the SFRD, the past quoted difference in the average SFRs of galaxies selected optically and in the near-IR disappears once the galaxies are subjected to a common near-IR magnitude limit, as we show below.

We have recently concluded a campaign to obtain deep near-IR imaging for fields in the \(z \sim 2\) optical survey (Steidel et al. 2004), allowing for a direct comparison of optical and near-IR selected galaxies. One result of this comparison is that \(K_s < 20\) (Vega) optically selected galaxies show similar space densities, stellar masses, and metallicities as \(K_s\)-bright galaxies in near-IR samples (Shapley et al. 2004). More recently, Adelberger et al. (2005) show that the correlation lengths for \(K_s\)-bright galaxies among optical and near-IR samples are similar, suggesting an overlap between the two sets of galaxies, both of which plausibly host the progenitors of massive elliptical galaxies in the local universe. These results suggest that near-IR bright galaxies have similar properties regardless of the method used to select them.

In this paper, we extend these results by examining the color distributions and X-ray properties of near-IR and optically selected galaxies at \(z \sim 2\) in the GOODS-North field (Giavalisco et al. 2004). The field is well-suited for this analysis given the wealth of complementary data available, including Chandra X-ray, ground-based optical and near-IR, and Spitzer IRAC (Infrared Array Camera) imaging. Multiwavelength data in a single field are particularly useful in that we can use a common method for extracting photometry that is not subject to the biases that may exist when comparing galaxies in different fields whose fluxes are derived in different ways. The addition of our rest-frame UV spectroscopic data in the GOODS-N field provides for a more detailed analysis than otherwise possible of the properties of galaxies as a function of selection technique. Furthermore, the GOODS-N field coincides with the Chandra Deep Field-North (CDF-N) region that has the deepest (2 Ms) X-ray data available (Alexander et al. 2003). The X-ray data allow for an independent estimate of bolometric SFRs, and the available depth allows more leeway in stacking smaller numbers of sources to obtain a statistical detection, as well as identifying AGNs to a lower luminosity threshold than possible in other fields that have shallower X-ray data.

The outline of the paper is as follows. In § 2 we describe the optical, near-IR, X-ray, and IRAC data and present the optical and near-IR selection criteria and X-ray stacking method. Color distributions, direct X-ray detections, and stacked results are examined in § 3. In § 4 we discuss the SFR distributions of optical and near-IR selected \(z \sim 2\) galaxies and their relative contributions to the SFRD, and the presence of a passively evolving population of galaxies. A flat \(\Lambda\)CDM cosmology is assumed with \(H_0 = 70\) km s\(^{-1}\) Mpc\(^{-1}\) and \(\Omega_\Lambda = 0.7\).

2. DATA AND SAMPLE SELECTION

2.1. Imaging

Optical \(Ugr\) images in the GOODS-N field were obtained in 2002 and 2003 April under photometric conditions using the KPNO and Keck I telescopes. The KPNO MOSAIC U-band image was obtained from the GOODS team (PI: Giavalisco) and was transformed to reflect \(U_g\) magnitudes (e.g., Steidel et al. 2004). The Keck I G- and R-band images were taken by us with the Low Resolution Imaging Spectrograph (LRIS; Oke et al. 1995; Steidel et al. 2004) and were oriented to provide the maximum overlap with the GOODS ACS and Spitzer survey region. The images cover 11’’ \(\times\) 15’’ with FWHM \(\approx 0.7\) to a depth of \(R \sim 27.5\) (3 \(\sigma\)). Image reduction and photometry were done following the procedures described in Steidel et al. (2003). We obtained deep B-band images of the GOODS-N field from a public distribution of Subaru data (Capak et al. 2004). The deep B-band data are acquired from the public distribution of the HST Advanced Camera for Surveys (ACS) data (Giavalisco et al. 2004). The B- and z-band data have \(5\) \(\sigma\) depths of 26.9 and 27.4 mag measured in 3’’ and 0’’2 diameter apertures, respectively. The \(K_s\) and J imaging was accomplished with the Wide Field Infrared Camera (WIRCam) on the Palomar Hale 5 m telescope (Wilson et al. 2003), providing 8’’7 \(\times\) 8’’7 coverage in the central portion of the GOODS-N field. The near-IR images cover \(\sim 43\%\) of the optical image. The images had FWHM \(\sim 170\) under photometric conditions and 3 \(\sigma\) sensitivity limits of \(\sim 22.6\) and \(\sim 24.1\) mag in the \(K_s\) and J bands, respectively. The near-IR data are described in detail by D. K. Erb et al. (2005, in preparation). The total area studied in the subsequent analysis is \(\sim 72.3\) arcmin\(^2\).

The procedures for source detection and photometry are described in Steidel et al. (2003). Briefly, \(Ugr\) magnitudes were
calculated assuming isophotal apertures that were adjusted to the $R$-band flux profiles. Source detection was done at $K_s$ band. $BzK$ and $J$ magnitudes are computed assuming the isophotal apertures adjusted to the $K_s$-band flux profiles, unless the $R$-band isophotes gave a more significant $K_s$ detection. In the analysis to follow, “$K_s$” and $J$ magnitudes are in Vega units. We use the conversion $K_{AB} = K_s + 1.82$. All other magnitudes are in AB units.

Fully reduced Spitzer IRAC mosaics of the GOODS-N field were made public in the first data release of the GOODS Legacy project (PI: Dickinson). The IRAC data overlap completely with our $K_s$-band image, but currently only two channels (either 3.6 and 5.8 μm or 4.5 and 8.0 μm) are available over most of the image. A small area of overlap has coverage in all four channels. The images are deep enough that source confusion is an issue. We have mitigated the effects of confusion noise by employing the higher spatial resolution $K_s$-band data to constrain source positions and deblend confused IRAC sources. We performed PSF photometry using the procedure described in Shapley et al. (2005).

### 2.2. Selection Criteria

#### 2.2.1. Optical Selection of Star-forming Galaxies

We have optically selected $z \sim 2$ galaxies in the GOODS-N field based on their observed $U_{G}/G_{R}$ colors (Adelberger et al. 2004; Steidel et al. 2004) to a limiting magnitude of $R = 25.5$. The selection criteria aim to select actively star-forming galaxies at $z \sim 2$ with the same range in UV properties and extinction as Lyman break galaxies (LBGs) at $z \sim 3$ (Steidel et al. 2003). “BX” galaxies are selected to be at redshifts $2.0 \leq z \leq 2.6$ using the following criteria:

\[
G - R \geq -0.2, \\
U_n - G \geq G - R + 0.2, \\
G - R \leq 0.2(U_n - G) + 0.4, \\
U_n - G \leq G - R + 1.0,
\]

and “BM” objects are selected to be at redshifts $1.5 \leq z \leq 2.0$ using the following criteria:

\[
G - R \geq -0.2, \\
U_n - G \geq G - R - 0.1, \\
G - R \leq 0.2(U_n - G) + 0.4, \\
U_n - G \leq G - R + 0.2
\]

(Adelberger et al. 2004; Steidel et al. 2004). For subsequent analysis, we will refer to BX and BM objects as those which are optically, or “BX/BM,” selected.

Optical color selection of $z \sim 2$ galaxies in the $11' \times 15'$ area of the GOODS-N field yielded 1360 BX and BM candidates, of which 620 lie in the region where we have complementary $J$- and $K$-band data ($\xi 2.1$), and 199 have $K_s < 21.0$. Follow-up spectroscopy with the blue channel of the Low Resolution Imaging Spectrograph (LRIS-B) yielded 147 redshifts for objects with $K_s$-band data (248 redshifts over the entire optical field). Of these 147 objects with redshifts and $K_s$-band data, 129 have $z > 1$, and 60 have $z > 1$ and $K_s < 21$. The mean redshift of the 60 BX/BM objects is $\langle z \rangle = 1.99 \pm 0.36$. The BX and BM selection functions (shown as shaded distributions in Fig. 1) have distributions with mean redshifts $\langle z \rangle = 2.2 \pm 0.3$ and $\langle z \rangle = 1.7 \pm 0.3$, respectively (Steidel et al. 2004), and the combination of these two samples comprises our BX/BM-selected $z \sim 2$ sample. In the analysis to follow, we designate an interloper as any object with $z < 1$.

#### 2.2.2. Near-IR Selection of Star-forming Galaxies

The near-IR properties of galaxies can be used both to target star-forming galaxies and to identify those with extremely red colors that may indicate passive evolution. To address the former issue, we have employed the “$BzK$” selection criteria of Daddi et al. (2004a) to cull objects in the GOODS-N field and directly compare with those selected on the observed optical properties of $z \sim 2$ galaxies. Daddi et al. (2004a) define the quantity “$BzK$”:

\[
BzK \equiv (z - K) - (B - z),
\]

star-forming galaxies with $z > 1.4$ are targeted by the following criterion:

\[
BzK \geq -0.2,
\]

in AB magnitudes. Of the 1185 sources with $z > 3 \sigma$ B, z, and $K$ detections and $K_s < 21, 221$ satisfy equation (4). The surface density of $BzK$ galaxies with $K_s < 21$ is $\sim 3$ arcmin$^{-2}$, similar to the surface density of BX/BM galaxies to a similar $K_s$-band depth. These star-forming $BzK$ galaxies will be referred to as “$BzK$/SF” galaxies, and their spectroscopic redshift distribution from our spectroscopic sample is shown in Figure 1. Our deep near-IR imaging allows us to determine the redshift distribution for $BzK$/SF galaxies with $K_s > 20$ (and which also satisfy the BX/BM criteria), and the results are shown in Figure 2. The mean
redshifts of the $K_s \leq 20$ and $K_s > 20$ distributions are $\langle z \rangle = 2.13 \pm 0.22$ and $\langle z \rangle = 2.03 \pm 0.41$, respectively, and agree within the uncertainty. We note, however, that the $BzK$/$SF$ criteria select $K_s \leq 20$ objects over a broader range in redshift ($1.0 \leq z \leq 3.2$) than $K_s \leq 20$ objects. This reflects the larger range in $BzK$ colors of $K_s > 20$ $BzK$/$SF$ galaxies compared with those having $K_s \leq 20$. Additionally, the photometric scatter in colors is expected to increase for fainter objects, so a broadening of the redshift distribution for $BzK$/$SF$ objects with fainter $K_s$ magnitudes is not surprising.

We emphasize that we only know the redshifts for $BzK$/$SF$ galaxies that also happen to fall in the BX/BM sample. In general, the true redshift distribution, $N^{BzK/SF}_0(z)$, of the $BzK$/$SF$ sample will be broader than the distributions shown in Figures 1 and 2, call them $N^{BzK/SF}_p(z)$, which are effectively convolved with the BX/BM selection function. For example, the rapid drop-off in $N^{BzK/SF}_p(z)$ for $z > 2.6$ (Fig. 2) may simply reflect the drop-off in the BX selection function for $z > 2.6$. However, the $N^{BzK/SF}_0(z)$ we derive here is similar to that of the photometric redshift distribution of K20 galaxies from Daddi et al. (2004a), which is subject to its own systematic errors, suggesting that a reasonable approximation is to take $N^{BzK/SF}_0(z) \approx N^{BzK/SF}_p(z)$.

### 2.2.3. Near-IR Selection of Passively Evolving Galaxies

In addition to the criteria above, several methods have been developed to select passively evolving high-redshift galaxies by exploiting the presence of absorption or continuum breaks in the spectral energy distributions (SEDs) of galaxies with dominant old stellar populations. The $BzK$ selection criteria

$$BzK < -0.2, \quad z - K > 2.5$$  \hspace{1cm} (5)

are designed to select passively evolving galaxies at $z > 1.4$ (Cimatti et al. 2004; Daddi et al. 2004a). One galaxy that has a secure $B$-band detection, and an additional 16 with $B$-band limits, satisfy these criteria, implying a surface density of $BzK/PE$ galaxies of 0.24 arcmin$^{-2}$ to $K_s = 21$. Galaxies selected by their $BzK$ colors to be passively evolving are referred to as “$BzK/PE$” objects. The redshift distribution of $BzK$/$PE$ galaxies, taken from the spectroscopic samples of Daddi et al. (2004a, 2005), shows that they mostly lie in the range $1.4 \leq z \leq 2$ (Fig. 1). We note that we may be incomplete for the $BzK$/$PE$ objects despite the very deep $B$-band data considered here and that these missing objects may be more easily selected using the $J - K_s > 2.3$ criteria discussed below (see also 2.4.2.3).

The $J - K_s$ color probes the age-sensitive Balmer and 4000 Å breaks for galaxies with redshifts $2.0 \leq z \leq 4.5$ (Fig. 3). The criterion

$$J - K_s > 2.3$$  \hspace{1cm} (6)

(Franx et al. 2003) can be used to select both passively evolving and heavily reddened star-forming galaxies with $E(B - V) > 0.3$. Galaxies satisfying this criterion are also referred to as distant red galaxies (DRGs). Star-forming galaxies are detected in $J$ and an additional 11 have $J$-band limits. The observed surface density of DRGs is $1.01 \pm 0.12$ arcmin$^{-2}$ to $K_s = 21$, in very good agreement with the surface density found by van Dokkum et al. (2004) and Förster Schreiber et al. (2004). The spectroscopic redshift distribution of DRGs from the four fields of the optical survey where we have deep $J$- and $K_s$-band imaging is shown in Figure 1 and is consistent with the redshift distributions found by van Dokkum et al. (2003, 2004) and Förster Schreiber et al. (2004). Star-forming and passively evolving DRGs are referred to as “DRG/PE” and “DRG/PE,” respectively. The depth of our $J$-band image implies that our sample of DRGs will be incomplete for those with $K_s = 21$. Therefore, we have limited ourselves to galaxies with $K_s < 21$ when comparing DRGs with $BzK$- and/or BX/BM-selected galaxies. We reconsider BX/BM and $BzK$ galaxies with $K_s > 21$ as noted below.
The optical magnitude distributions for galaxies with $K_s < 21$ are shown in Figure 4. The catalog of BX/BM galaxies is restricted to $R < 25.5$. However, our optical imaging is significantly deeper ($R = 27.5$; 3 $\sigma$), allowing us to extract optical magnitudes for galaxies much fainter than those in the BX/BM catalog. Most of those galaxies with $R > 25.5$ are DRGs. The nature of optically faint DRGs is discussed in § 4.2.

For most of the analysis that follows, either we use only the spectroscopically confirmed subsample of BX/BM galaxies, or we apply our knowledge of the contamination fraction of the photometric sample to deduce any inferred quantities. The small available spectroscopic samples using the near-IR criteria prevent us from applying similar corrections when deducing properties for the near-IR samples.

2.3. X-Ray Data and Stacking Method

One focus of this paper is to draw comparisons between galaxies selected by the techniques described above by using their stacked X-ray emission as a proxy for their bolometric SFRs. X-ray stacking allows us to determine instantaneous bolometric SFRs in a manner that is independent of extinction and the degeneracies associated with stellar population modeling. For example, the average reddening of rest-frame UV selected galaxies of $E(B-V) \sim 0.15$ implies a column density of $N_{HI} \sim 7.5 \times 10^{20}$ cm$^{-2}$, assuming the Galactic calibration (Dipas & Savage 1994). Absorption in the rest-frame 2–10 keV band is negligible for these column densities. The X-ray data are taken from the Chandra 2 Ms survey of the GOODS-N field (Alexander et al. 2003). We made use primarily of the soft-band (0.5–2.0 keV) data for our analysis, but we also include hard-band (2.0–8.0 keV) data to examine the nature of directly detected X-ray sources. The data are corrected for vignetting, exposure time, and instrumental sensitivity in producing the final mosaicked image. The final product has a soft-band on-axis sensitivity of $\sim 2.5 \times 10^{-17}$ ergs s$^{-1}$ cm$^{-2}$ (3 $\sigma$), sufficient to directly detect $L_{2-10 keV} > 9.3 \times 10^{41}$ ergs s$^{-1}$ objects at $z \sim 2$, corresponding to an SFR of $\sim 190 M_{\odot}$ yr$^{-1}$.

The stacking procedure followed here is the same as that discussed in Reddy & Steidel (2004). Apertures used to extract X-ray fluxes had radii set to $2 S_{0}$ for sources within $6'$. The average Chandra pointing origin, and set to the 50% encircled energy radius for sources with off-axis angles greater than $6'$ (Feigelson et al. 2002). X-ray fluxes were computed by adding the counts within apertures randomly dithered by $0''5$ at the galaxy positions. Background estimates were computed by randomly placing the same sized apertures within $5''$ of the galaxy positions, careful to prohibit the placing of a background aperture on a known X-ray detection. This procedure of placing random apertures was repeated 1000 times. The mean X-ray flux of a galaxy is taken to be the average of all the flux measurements from the $0''5$ dithered apertures, and the background noise is taken to be the dispersion in fluxes measured from the background apertures. We applied aperture corrections to the fluxes and assumed count rate to flux conversions based on the results compiled in Table 7 of Alexander et al. (2003), a photon index $\Gamma = 2.0$, and a Galactic absorption column density of $N_{HI} = 1.6 \times 10^{20}$ cm$^{-2}$ (Stark et al. 1992). Poisson errors dominate the uncertainties in flux.

3. RESULTS

3.1. Direct X-Ray Detections

Of the 221 BzK/4 candidates with $K_s < 21, 32$ (14%) have an X-ray counterpart within $1''5$ (Alexander et al. 2003), with a $\sim 0.22$% probability for chance superposition. The X-ray detection fractions are 24%, 6%, and 26% for the BzK/PE, BX/BM, and DRG samples, respectively, and are summarized in Table 1. Eleven of the 36 directly detected BzK sources (32 in the BzK/PE sample and four in the BzK/PE sample) would not have been detected with the sensitivity of the shallower 1 Ms data in the GOODS-South field studied by Daddi et al. (2004a). After taking into account the sensitivity difference, we find a direct X-ray detection rate comparable to that of Daddi et al. (2004a) of $\sim 11%$. Figure 5 shows the X-ray/optical flux ratios $[\log (f_{X}/f_{opt})]$ for sources in all four samples (BX/BM, BzK/PE, BzK/4, and DRG) directly detected in the Chandra hard band ($2-8$ keV). Hard-band detections must be AGNs if they are at $z \sim 2$, since starburst galaxies with no accretion activity are expected to have little flux at rest-frame energies of 6–20 keV. Indeed, the X-ray/optical flux ratios for directly detected hard-band sources lie in the region typically populated by AGNs (shaded area of Fig. 5). A smaller fraction of galaxies with direct hard-band detections [and the three sources with the smallest $\log (f_{X}/f_{opt})$] are spectroscopically confirmed interlopers at $z < 1$. From Table 1, it is easy to see that much of the AGN contamination in star-forming samples of galaxies (e.g., BX/BM, BzK/4) occurs for magnitudes $K_s < 20$.

Figure 5 only shows those X-ray sources with hard-band detections. Eleven additional sources had direct soft-band (0.5–2.0 keV) detections but no hard-band detections. Of these 11, five sources have $R > 22.0$, $f_{0.5-2.0 keV} \leq 0.1 \times 10^{-15}$ ergs cm$^{-2}$ s$^{-1}$, and $\log (f_{X}/f_{opt}) < -1$, indicating that they may be starburst galaxies. These five sources and their properties are summarized in Table 2. Three of the five sources have spectra taken by us or by Barger et al. (2003) indicating no obvious AGN spectral features. These sources may be rapidly star-forming galaxies and for fairness we include them in the stacking analysis, as indicated below and in Table 1.
It is interesting to also consider the rest-frame near-IR properties of the directly detected X-ray sources as indicated by their Spitzer IRAC colors. Figure 6 shows the 3.6–5.8 μm color as a function of 3.6 μm magnitude for all samples considered here. There is a clear segregation in the IRAC colors of X-ray detections where they show, on average, brighter IRAC magnitudes and redder IRAC colors when compared with the colors of star-forming galaxies in the BX/BM and BzK/SF samples. Such a trend might be expected if the rest-frame near-IR light from the X-ray sources is dominated by thermal continuum from circum-nuclear dust heated by the AGN. The increase in flux density across the IRAC bands for AGNs has been seen for ERO (extremely red object) samples at redshifts z ~ 1–3 (Frayer et al. 2004), similar to what is observed here. Finally, the five objects listed in Table 2 have m3.6–5.8 μm ~ −0.35 to 0.35 and m3.6,4.5 μm = 20.2–22.0, lying in the same region of IRAC color space as some of the star-forming BX/BM and BzK/SF candidates.

At times in the following analysis, we also consider submilimeter galaxies (SMGs) and their relation to optical and near-IR selected objects. These heavily star-forming objects are generally associated with directly detected X-ray sources, and we reconsider the X-ray emission from these sources as pointed out below. Unless otherwise stated, however, we have excluded all directly detected hard-band X-ray sources from the analysis under the assumption that their X-ray emission is contaminated by AGNs.

3.2. Overlap between Samples

Galaxies selected solely by the presence of some unobscured star formation (BX/BM selection), as well as those selected by some combination of stellar mass and star formation (DRG and BzK selection), can be distinguished by their observed near-IR color distributions (Fig. 7). The mean (z − K)AB color for BX/BM galaxies is ~0.54 mag bluer than the BzK/SF sample, just within
the 1 $\sigma$ dispersion of both samples. This difference in average $(z - K)_{AB}$ color between BX/BM and BzK/SF galaxies partly stems from the fact that the width of the BzK selection window below $(z - K)_{AB} = 1$ narrows to the point where photometric scatter becomes increasingly important in determining whether a galaxy with blue colors \[i.e., (z - K)_{AB} < 1\] is selectable with the BzK/SF criteria.\(^4\) On the other hand, the BX/BM criteria are less efficient than BzK selection for galaxies with $(z - K)_{AB} \gtrsim 1.6$. BX/BM galaxies with red near-IR colors are systematically fainter in the optical than those with blue near-IR colors (Fig. 8), reflecting both the correlation between $R$ and $z$, as these filters lie close in wavelength, and the $K_s$ magnitudes are from Barger et al. (2003).

Separately, DRGs have a very red $(z - K)_{AB} = 2.49 \pm 0.78$. Approximately 10% of $z > 1.4$ BzK/SF galaxies also have $J - K_s > 2.3$ (Fig. 9), similar to that found by Daddi et al. (2004a). The fact that there is some, albeit small, overlap between the BzK/SF and DRG samples is not surprising since the two criteria can be used to target reddened galaxies and both have redshift distributions that overlap in the range $2.0 < z < 2.6$ (Fig. 1). The DRG fraction among BzK-selected galaxies does not change appreciably if we add in the BzK/PE sources—only 5 of 17 BzK/PE galaxies have $J - K_s > 2.3$—as the BzK/PE galaxies are mostly at redshifts lower than the DRGs ($z \leq 2$). Finally, we note that DRGs include objects with much redder $(z - K)_{AB}$ colors than found among BX/BM and BzK/SF/PE galaxies, i.e., those with $(z - K)_{AB} > 3$. The absence of these galaxies from star-forming selected samples is discussed in § 4.2.

Note.—Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.

\(^a\) Soft-band fluxes are from Alexander et al. (2003), and Cousins $R$ magnitudes are from Burger et al. (2003).

\(^b\) Defined as $\log (f_z/f_k) = \log f_z + 5.50 + R/2.5$ (Hornschemeier et al. 2001).

Fig. 6.—Spitzer IRAC 3.6–5.8 $\mu$m color vs. 3.6 $\mu$m magnitude (in AB units) for all samples considered here, with emphasis on directly detected X-ray sources \[large circles\]. These direct detections generally have brighter IRAC magnitudes and redder colors than star-forming BX/BM and BzK/SF galaxies, likely due to thermal continuum from circumnuclear dust proximate to the AGN.

Fig. 7.—The $z - K$ color distribution for BX/BM, star-forming BzK, and DRG galaxies to $K_s = 21$. The mean $z - K$ color of galaxies becomes redder for the BX/BM to BzK to DRG samples. BX/BM selection is more efficient in selecting objects with blue $(z - K)_{AB} \lesssim 1$, and DRG selection is more efficient in selecting objects with very red $(z - K)_{AB} > 3$. The BzK criteria spans the middle range of $(z - K)_{AB}$ color. The small solid histogram shows the arbitrarily normalized distribution in $(z - K)_{AB}$ color for passively evolving BzK galaxies. [See the electronic edition of the Journal for a color version of this figure.]

TABLE 2

| $\alpha$ (J2000.0) | $\delta$ (J2000.0) | Sample | $z$ | $f_{0.5-2.0\,keV}$ $^a$ | $K_s$ | $R^b$ |
|-------------------|-------------------|--------|----|-----------------|-------|-------|
| 12 36 21.95............ | 62 14 15.5 | BzK/SF | 1.38 | 0.02 | 18.95 | 23.1 |
| 12 36 52.75............ | 62 13 54.8 | BX/BM | 1.36 | 0.03 | 19.54 | 22.1 |
| 12 36 53.46............ | 62 11 40.0 | BX/BM, BzK/SF | ... | 0.11 | 18.65 | 22.7 |
| 12 36 56.89............ | 62 11 12.1 | BzK/SF | ... | 0.02 | 20.50 | 23.8 |
| 12 37 03.70............ | 62 11 22.6 | BX/BM, BzK/SF | 1.72 | 0.04 | 19.92 | 23.4 |

For all samples considered here, with emphasis on directly detected X-ray sources \[large circles\]. These direct detections generally have brighter IRAC magnitudes and redder colors than star-forming BX/BM and BzK/SF galaxies, likely due to thermal continuum from circumnuclear dust proximate to the AGN.
We can directly quantify the overlap between BzK/SF and BX/BM galaxies. Figure 10a shows the fraction of BzK/SF galaxies satisfying the BX/BM criteria, and Figure 10b shows the fraction of BX/BM galaxies satisfying the BzK/SF criteria. Most of the contamination of the BzK/SF sample (that we know of) is from X-ray detected AGNs (‡3.1), while most of the contamination of the BX/BM sample is from low-redshift interlopers (Table 3). Both sources of contamination tend to occupy the bright end of the K-band apparent magnitude distribution. We also show the overlap fractions in Figure 10 excluding X-ray detected AGNs and interlopers. The BX/BM criteria recover an increasing fraction of BzK/SF-selected sources proceeding from Ks < 20 galaxies (∼60% recovery fraction) to Ks = 21 galaxies (∼80% recovery fraction) after excluding directly detected X-ray sources that are likely AGNs (‡3.1). Conversely, the BzK/SF criteria recover ∼80% of spectroscopically confirmed BX/BM galaxies at z > 1.4 and are evidently effective at recognizing most of the BX/BM low-redshift interlopers that tend to occupy the bright end of the K-band apparent magnitude distribution. This result stems from the fact that low-redshift interlopers

| Ks Range | Nphot | Nspec | Nz<1 | f<1 |
|----------|-------|-------|------|-----|
| Ks ≤ 20.0 | 61 | 18 | 7 | 0.39 |
| 20.0 < Ks ≤ 20.5 | 58 | 23 | 2 | 0.09 |
| 20.5 < Ks ≤ 21.0 | 82 | 30 | 3 | 0.10 |
| 21.0 < Ks ≤ 21.5 | 101 | 32 | 2 | 0.06 |
| 21.5 < Ks ≤ 22.0 | 141 | 29 | 3 | 0.10 |

a Number of photometric BX/BM candidates.
b Number of candidates with spectroscopic redshifts.
c Number of interlopers.
d Interloper fraction.

TABLE 3
INTERLOPER CONTAMINATION OF THE BX/BM SAMPLE
tend to have bluer colors than necessary to satisfy the BzK/SF criteria.

Figures 11 and 12 show that a significant portion of BzK/SF galaxies missed by BX/BM selection and a significant portion of BX/BM galaxies missed by BzK/SF selection have colors that place them within ±0.2 mag of the selection windows, which is comparable to the photometric uncertainties. The BX/BM criteria likely miss some BzK/SF galaxies because of some failure of the criteria, but because we cannot measure photometry with infinite precision. The trend from lower (60%) to higher (80%) recovery rate shown in Figure 11a reflects the fact that a greater percentage of $K_s < 20$ BzK/SF galaxies have redder $G - R$ colors (when compared with $K_s > 20$ BzK/SF galaxies) than required to satisfy the BX/BM criteria (Fig. 11). There are some BzK/SF galaxies that have very red $G - R \geq 0.8$ colors. As we show in §4, these red $G - R$ galaxies would have an average bolometric SFR similar to BzK/SF galaxies with bluer $G - R$ colors if they are at similar redshifts, $z \sim 2$. Therefore, if these red objects are at $z \sim 2$, then the correlation between $G - R$ and reddening, as quantified by the Calzetti et al. (2000) law, would appear to fail. Photometric scatter will also reduce the effectiveness of the BzK criteria in selecting BX/BM galaxies (Fig. 12). We can account for most of the photometric incompleteness using the more sophisticated analysis of Reddy et al. (2005).

Our deep K-band data allow us to investigate the efficiency of BzK/SF selection to fainter $K$ magnitudes than previously possible. Figure 13 shows the BzK colors of BX/BM galaxies with spectroscopic redshifts $1.4 < z < 2.6$ for three bins in $K_s$ magnitude. The BzK/SF criteria were designed to select relatively massive galaxies with $K_s < 20$, but they become slightly less efficient in culling $K_s > 21$ galaxies: 10 of 49 (~20%) BX/BM galaxies with spectroscopic redshifts $1.4 < z < 2.6$ and $K_s > 21$
do not satisfy the $BzK/SF$ criteria. Furthermore, we note that 
$\sim 11\% (61/544)$ of BX/BM candidates that fall in the region with 
$K$-band data are undetected to $K_s = 22.5$ ($3\sigma$). The $K$-band lim-
its for these galaxies suggest that they are younger star-forming 
systems with $(z - K)_{	ext{LAB}} \lesssim 1$, below which the $BzK/SF$ criteria 
drop in efficiency, as discussed above. We remind the reader that 
many of the $BzK/SF$ objects not appearing in the BX/BM sample 
may be missed by the BX/BM criteria simply because of photo-
metric errors. BX/BM galaxies missed by the $BzK/SF$ criteria may 
be missed not because of intrinsic differences in the objects, but 
simply because of photometric scatter or because of the difficulty 
in obtaining very deep $K_s$-band data.

Turning to $J - K_s > 2.3$ galaxies, we show the optical colors of 
DRGs with $R < 25.5$ in Figure 11, and the near-IR colors of the 
$74\%$ of DRGs with $z$-band detections in Figure 12. The optical 
criteria are particularly inefficient in selecting $J - K_s > 2.3$ 
sources: $9$ of $73 (12\%)$ DRGs in the GOODS-N field satisfy BX, 
BM, or LBG selection. This fraction is similar to the overall de-
tection rate found by D. K. Erb et al. (2005, in preparation) for 
the four fields in the $z \sim 2$ optical survey with deep $J$- and 
$K$-band data. The LBG criteria can be used to select some DRGs 
since $z \sim 2$ galaxies with a Calzetti reddened constant star for-
mation SED with $E(B - V) \gtrsim 0.3$ are expected to lie in the color 
space occupied by $z \sim 3$ LGBs. A greater fraction ($\sim 30\%$) of 
DRGs satisfy the $BzK/SF$ criteria (Fig. 12) since these criteria 
select objects with developed spectral breaks and with redshifts 
that fall in the range probed by DRG selection (see Fig. 1). We 
note that DRGs with $B$-band limits cluster in the region of color 
space expected for passively evolving $z > 1.4$ galaxies (Fig. 12). 
These DRGs have little, if any, current star formation (see § 4.2).

3.3. Stacked X-Ray Results

The X-ray data are not sufficiently sensitive to detect individual 
galaxies with $\text{SFR} \lesssim 190 M_\odot \text{yr}^{-1}$ ($3\sigma$). We can, however, 
stack the X-ray data for subsets of galaxies below the sensitivity 
threshold to determine their average X-ray emission. The influ-
ce of AGNs in any X-ray stacking analysis is a concern. The 
softness of a stacked signal provides some circumstantial evi-
dence for X-ray emission due primarily to star formation (e.g., 
von Dokkum et al. 2004; Daddi et al. 2004a; Laird et al. 2005). 
UV line signatures and radio emission can provide additional con-
straints on the presence of AGNs (e.g., Reddy & Steidel 2004).

We typically removed all directly detected X-ray sources from the 
optical and near-IR samples before running the stacking simu-
lations, except as noted below and in Table 2 when considering 
X-ray detected sources that may be star-forming galaxies. Our 
method of excluding other X-ray detected sources ensures that 
luminous AGNs do not contaminate the stacked signal. Indirect 
evidence suggests that less luminous AGNs do not contribute 
significantly to the stacked signal. First, the stacked signal has 
no hard-band (2–8 keV) detection, indicating that the signal is 
softer than one would expect with a significant AGN contribu-
tion. Second, the availability of rest-frame UV spectra for many 
of the BX/BM objects provides an independent means of identi-
fying AGNs. There is one source whose spectrum shows high-
ionization emission lines in the rest-frame UV, but no X-ray 
detection in the Chandra 2 Ms data. Removing this X-ray–faint 
AGN source does not appreciably affect the stacked X-ray flux. 
In addition, Reddy & Steidel (2004) examined the very same 
BX/BM data set used here and found a very good agreement be-
tween dust-corrected UV, radio, and X-ray inferred SFRs for the 
sample, suggesting star formation as the dominant mechanism in 
producing the observed multwavelength emission. Finally, the 
local hosts of low-luminosity AGNs have stellar populations char-
acteristic of passively evolving early-type galaxies (Kauffmann 
et al. 2003). In § 4.2 we show that passively evolving galaxies at 
$z \sim 2$ have little or no detectable X-ray emission, implying that 
low-level accretion activity in these systems does little to alter the 
X-ray emission relative to that produced from star formation. The 
absence of X-ray emission from these passively evolving galaxies 
also suggests that low-mass X-ray binaries contribute little X-ray 
emission in star-forming galaxies when compared with the emis-
ション produced from more direct tracers of the current SFR, such 
as high-mass X-ray binaries.

Stacking results for the samples (to $K_s = 22.5$) are summa-
rized in Figure 14 and Table 1. Figure 14a includes all photometri-
cally selected $BzK/SF$ and DRG galaxies and all spectroscopically 
confirmed $z > 1$ BX/BM galaxies. Figure 14b includes only 
those $BzK/SF$ galaxies with spectroscopic redshifts $z > 1$, all of 
which also satisfy the BX/BM criteria. All direct X-ray detec-
tions have been excluded in making Figure 14. The distributions 
do not change appreciably if we only consider the X-ray flux 
of $BzK/SF$ galaxies spectroscopically confirmed to lie at $z > 1$ 
(Fig. 14b). Removing the one spectroscopic $z > 1$ AGN unde-
tected in X-rays does little to change the X-ray luminosity distribu-
tions. The luminosity distributions agree well between the three 
samples over a large range in $K_s$, magnitude, with $K_s < 20$ gal-
axies exhibiting the largest X-ray luminosities by a factor of 2–3 
when compared with fainter $K_s > 20.5$ galaxies.

4. DISCUSSION

In this section we first present the X-ray inferred average 
bolometric SFRs for galaxies in the BX/BM, $BzK/SF/PE$, and 
DRG samples and compare our results with other X-ray stacking 
analyses. Unless stated otherwise, we exclude hard-band X-ray
AGN sources from the analysis of the SFRs. The SFRs are interpreted for galaxies as a function of their near-IR colors, and we assess the ability of optical surveys to single out both heavily reddened and massive galaxies. We identify passively evolving galaxies at $z \sim 2$ from their red near-IR colors and discuss plausible star formation histories for these galaxies using the X-ray data as an additional constraint. Finally, we discuss the contribution of BX/BM, BzK/SF, and DRG galaxies to the SFRD at $z \sim 2$, taking into account the overlap between the samples and their respective redshift distributions.

4.1. Star Formation Rate Distributions

4.1.1. Star Formation Rates and Comparison with Other Studies

We estimated the SFRs for galaxies in our samples using the Ranalli et al. (2003) calibration between X-ray and FIR luminosity. This calibration reproduced the SFRs based on independent star formation tracers for $z \sim 2$ galaxies (Reddy & Steidel 2004), so we are confident in using it here. The SFR distributions for BX/BM, BzK, and DRG galaxies are shown in Figure 15, where we have added the five directly detected soft-band X-ray sources in Table 2 that may be star-forming galaxies. The SFRs are summarized in Table 1. The mean SFR of $K_s < 20$ galaxies is $\sim 90-140 \ M_{\odot} \ yr^{-1}$ and is a factor of 2–3 times larger than galaxies with $K_s > 20.5$. For comparison, Daddi et al. (2004a) found an average SFR of K20 galaxies in the GOODS-S field of 190 $M_{\odot} \ yr^{-1}$ (including one likely star-forming galaxy directly detected in X-rays). This is somewhat higher than our value of 110 $M_{\odot} \ yr^{-1}$ for $K_s < 20$ BzK/SF galaxies. This discrepancy could simply result from field-to-field variations, smaller sample statistics, or the lower sensitivity of the X-ray data in the GOODS-S field compared to GOODS-N. With the Chandra 2 Ms data, we are able to exclude directly detected X-ray sources down to a factor of 2 lower threshold than was possible with the 1 Ms data in the GOODS-S field. If we add back those $K_s < 20$ X-ray BzK/SF galaxies that would have been undetected in the 1 Ms data to the stacking analysis, we obtain an average SFR of 160 $M_{\odot} \ yr^{-1}$, more in line with the Daddi et al. (2004a) value of 190 $M_{\odot} \ yr^{-1}$.

A similar stacking analysis by Rubin et al. (2004) indicates that $K_s < 22$ DRGs have SFRs of $\sim 280 \ M_{\odot} \ yr^{-1}$, corrected for the difference in SFR calibration used here and in Rubin et al. (2004). This very high value is likely a result of the shallow X-ray data (74 ks) considered in that study; the depth of their X-ray data precludes the removal of most of the X-ray sources that are directly detected in the 2 Ms X-ray survey. If we include those X-ray sources that would have been undetected in the 74 ks data, assuming a mean redshift of $(z) = 2.4$, the average SFR for the DRGs with $K_s < 21$ is 250 $M_{\odot} \ yr^{-1}$. Therefore, much of the difference in the SFRs can be attributed to unidentified AGNs in the shallower X-ray surveys contaminating estimates of the SFR. If Figure 15 is any indication, then adding DRGs with 21 < $K_s$ < 22 to the stack would decrease this average SFR. Variance of the fraction of DRG/PE galaxies between fields may also affect the average SFR: a greater fraction of DRG/PEs in the GOODS-N field, $\sim 25\%$ (3/13) of which have $K_s < 20$, will lead to a lower average SFR for $K_s < 20$ DRGs. As we show in §4.4.2, there are clearly some number of very reddened galaxies with large SFRs (e.g., SMGs) among DRGs (and among the BX/BM and BzK/SF samples). Regardless, these calculations underscore the importance of factoring in the differing sensitivity limits of the various X-ray surveys before comparing results. The strong dependence of SFR on $K_s$ magnitude (Fig. 15) also suggests that fair comparisons of the SFRs of galaxies selected in different surveys can only be made between objects with similar rest-frame optical luminosities.

Our analysis is advantageous as we are able to compare the SFRs of galaxies within the same field, employing the same multiband wavelength data (to the same sensitivity level) and the same photometric measurement techniques, for a consistent comparison. The inferred average SFRs of BzK/SF and DRG galaxies are remarkably similar to that of optically selected galaxies once the samples are restricted to similar $K_s$ magnitudes. The previously noted discrepancies in X-ray inferred SFRs of BzK/SF, DRG, and BX/BM galaxies are therefore likely a result of a mismatch between X-ray survey limits and near-IR magnitude ranges. Field-to-field variations may also partly account for the previously observed discrepancies.

4.1.2. Dependence of SFR on $(z - K)_{\text{AB}}$ Color

We began our analysis by noting the differences between the $(z - K)_{\text{AB}}$ color distributions of optical and near-IR selected galaxies (Fig. 7). Figure 15 indicates that despite these near-IR color differences, the BX/BM, BzK, and DRG galaxies have very similar average SFR distributions as a function of $K_s$ magnitude. Another proxy for stellar mass is the $(z - K)_{\text{AB}}$ or $R - K_s$ color (e.g., Shapley et al. 2005), as it directly probes the strength of the Balmer and 4000 Å breaks. Figure 16 shows the inferred average SFRs of optical and near-IR selected galaxies as a function of their $(z - K)_{\text{AB}}$ color, excluding all directly detected X-ray sources. Within any single sample, objects with red $(z - K)_{\text{AB}}$ colors up to $(z - K)_{\text{AB}} \sim 3$ have the largest SFRs. The red $(z - K)_{\text{AB}}$ color for these objects with high SFRs likely results from a developed spectral break (due to an older stellar population) combined.

5 Adding the five sources in Table 2 does not appreciably affect Fig. 16.
with the effects of dust. In fact, Figure 17 illustrates the tendency for BX/BM objects with spectroscopic redshifts \( z > 1 \) and red \( (z - K)_{AB} \) colors to have larger attenuation [as parameterized by \( E(B - V) \)], on average, than those with bluer \( (z - K)_{AB} \) colors. The turnover in the inferred SFR around \( (z - K)_{AB} \approx 3 \) is discussed in the next section.

Figure 16 suggests that optically selected BX/BM galaxies may have systematically higher SFRs than \( BzK \) and DRG galaxies with similar \( (z - K)_{AB} \) colors, perhaps indicating that the stacked sample for \( BzK/SF \) and DRG galaxies includes those that are passively evolving. This may be particularly true of DRGs, quite a few of which only have \( B \)-band limits and which cluster in the \( BzK \) color space occupied by passively evolving galaxies (Fig. 12). We can assess the dispersion in SFRs by separately stacking galaxies that are expected to be currently star-forming based on their colors and those that are not. For example, the average SFR computed for \( BzK/SF \) galaxies that are not selected by the BX/BM criteria (of which \(~70\%\) are within 0.2 mag of the BX/BM selection windows) is \(~70\, M_\odot\, yr^{-1}\), comparable to the average SFR of all \( BzK/SF \) galaxies with \( K_s < 21 \). In summary, star-forming \( BzK \) galaxies have similar SFRs regardless of whether or not they satisfy the BX/BM criteria. The BX/BM criteria miss some \( BzK/SF \) galaxies either because of photometric scatter or because their optical colors are not indicative of their reddening. It is worth noting that photometric scatter works both ways: some sources with intrinsic colors satisfying the BX/BM criteria will be scattered out of the BX/BM selection windows and some whose colors do not satisfy the BX/BM criteria will be scattered into the BX/BM selection windows, although the two effects may not equilibrate (Reddy et al. 2005). The incompleteness of the BX/BM and \( BzK/SF \) criteria with respect to all star-forming galaxies at \( z \sim 2 \) simply reflects our inability to establish perfect selection criteria immune to the effects of photometric scatter and SED variations while at the same time efficiently excluding interlopers (e.g., Adelberger et al. 2004). However, the advantage of spectrophotometric optical surveys is that their selection functions can be quantified relatively easily (e.g., Adelberger et al. 2004; Reddy et al. 2005).

4.1.3. Optical Selection of Reddened Star-forming Galaxies

Naively, one might interpret the inferred SFRs as a function of \( (z - K)_{AB} \) color combined with the results shown in Figure 8 to suggest that BX/BM selection may miss the most actively star-forming galaxies at \( z \sim 2 \). We can interpret the similarity in SFRs of BX/BM and \( BzK/SF \) galaxies in the context of their reddening, as parameterized by their rest-frame UV spectral slopes, \( E(B - V) \). Daddi et al. (2004a) show that the reddening vector is essentially parallel to the \( BzK \) limit defined by equation (4), implying that \( BzK \) selection should be sensitive to galaxies with higher extinction (and presumably higher SFRs) than found among BX/BM-selected galaxies \([i.e., E(B - V) \geq 0.3]\). However, the similarity in the average SFRs of BX/BM and \( BzK/SF \) galaxies suggests several possibilities. First, we noted above that \( BzK/SF \) galaxies not selected by the BX/BM criteria have SFRs similar to those that do satisfy the BX/BM criteria. 6 Consequently, \( BzK/SF \) galaxies with large SFRs that do not satisfy the BX/BM criteria because they truly have \( E(B - V) > 0.3 \) may not exist in sufficient numbers to significantly change the average SFRs for all \( BzK/SF \) galaxies that do not satisfy the BX/BM criteria. Adelberger & Steidel (2000) and Laird et al. (2005) find that optically selected galaxies with \( z \geq 1 \) show no correlation between their rest-frame UV luminosities and their obscuration, implying that on average the redder (more obscured) galaxies have higher bolometric SFRs than galaxies with less reddening. Therefore,

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6 Those \( BzK/SF \) galaxies with \( G - R \gtrsim 1 \) and blue \( U_g - G \lesssim 1 \) have optical colors that are similar to the colors expected for lower redshift (\( z \lesssim 1 \)) galaxies (e.g., Adelberger et al. 2004). So, if these galaxies are truly low-redshift galaxies, then their inferred SFRs would be even lower.
the similarity in the average X-ray inferred SFRs of BX/BM and BzK/SF galaxies suggests that there are not large numbers of galaxies with \( E(B-V) \geq 0.4 \) (i.e., if there were a large number of such heavily reddened objects, their bolometric SFRs would imply X-ray luminosities large enough to be directly detected in the soft-band X-ray data, and very few likely star-forming galaxies at these redshifts are directly detected in the soft band).

Second, studies of the UV emission from SMGs suggest that heavily reddened galaxies may have rest-frame UV spectral properties, such as their range in \( E(B-V) \), similar to those that are forming stars at modest rates, implying that the correlation between \( E(B-V) \) and bolometric SFR (e.g., from the Meurer et al. 1999 and Calzetti et al. 2000 laws) breaks down for the most actively star-forming galaxies (e.g., Chapman et al. 2005). Table 4 summarizes the properties of the nine known radio-selected SMGs with \( S_{850} \geq 5 \) mJy in the GOODS-N field that overlap with our near-IR imaging (Chapman et al. 2005; Wang et al. 2004). Also listed are two (pair) sources with \( S_{500} \geq 4 \) mJy taken from Chapman et al. (2005) and Wang et al. (2004). Of the seven SMGs with redshifts \( 1.4 < z < 2.6 \), three satisfy the BX/BM criteria. The detection rate of \( \sim 40\% \) is similar to the detection rate of SMGs with BX/BM colors found by Chapman et al. (2005). The mean bolometric luminosity of the five SMGs is \( \langle L_{\text{bol}} \rangle \sim 9 \times 10^{12} \, L_{\odot} \) as inferred from their submillimeter emission, corresponding to an SFR of \( \sim 1500 \, M_{\odot} \, \text{yr}^{-1} \) using the Kennicutt (1998) relation. Despite their large bolometric luminosities, the three SMGs with redshifts in our sample have dust-corrected UV SFRs of \( 14 - 28 \, M_{\odot} \, \text{yr}^{-1} \). In these cases, the UV emission may come from a relatively unobscured part of the galaxy or may be scattered out of the optically thick dusty regions (Chapman et al. 2005). The BzK/SF criteria cull five of the seven SMGs with redshifts \( 1.4 < z < 2.6 \). Therefore, at least in the small sample of SMGs examined here (irrespective of their X-ray properties), the BX/BM and BzK/SF samples host an approximately equal number of SMGs. Finally, as we show below, galaxies with the most extreme \( (z-K)_{\text{AB}} \) color (i.e., \( (z-K)_{\text{AB}} > 3 \)) are red not because they are obscured by dust, but because they have little or no current star formation. It is therefore not surprising that such objects are not identified by criteria designed to select star-forming galaxies.

4.2. Passively Evolving Galaxies at \( z \sim 2 \)

4.2.1. Near-IR Colors

We now turn to galaxies in our samples that appear to have little or no current star formation. DRGs have SFRs that are comparable to those of BzK/SF and BX/BM galaxies with similar near-IR colors for \( (z-K)_{\text{AB}} < 3 \). However, stacking the 13 DRGs with \( (z-K)_{\text{AB}} \geq 3 \) results in a nondetection with an upper limit of \( 15 \, M_{\odot} \, \text{yr}^{-1} \) (Fig. 16). The X-ray emission from the 17 BzK/PE galaxies shows a similar turnover in the inferred average SFR around \( (z-K)_{\text{AB}} \sim 3 \) (Fig. 16). The BzK colors of the DRGs (most of which only have B-band limits) lie in the BzK color space expected for passively evolving galaxies (Fig. 12). The stacking analysis confirms that these red DRGs and BzK/PE galaxies have little current star formation compared with DRGs and BzK/PE galaxies with bluer near-IR colors (Fig. 16). A similar X-ray stacking analysis by Brusa et al. (2002) yields no detection for passive EROs in the K20 survey from the Chandra Deep Field–South data.

The average \( J-K_{\text{s}} \) color of the 13 passively evolving DRGs [with \( (z-K)_{\text{AB}} > 3 \)] is \( \langle J-K_{\text{s}} \rangle = 2.98 \pm 0.59 \) and is comparable to the average \( J-K_{\text{s}} \) color of DRGs with bluer \( (z-K)_{\text{AB}} \) colors, implying that the \( J \) band is in close proximity to the Balmer and 4000 Å breaks or that the band encompasses the breaks completely. This will occur for galaxies with a mean redshift \( \langle z \rangle \sim 1.88 - 2.38 \) (Fig. 3). In these cases, the \( (z-K)_{\text{AB}} \) color will be more effective than the \( J-K_{\text{s}} \) color in culling those galaxies with developed spectral breaks. The fraction of passively evolving DRGs inferred from their lack of X-ray emission is \( 13/54 \sim 24\% \), which is in reasonable agreement with the passively evolving DRG fraction of \( \sim 30\% \) found by Förster Schreiber et al. (2004) and Labbé et al. (2005).
Alternatively, galaxies with $2 < (z - K)_{AB} < 3$ must still be forming stars at a prodigious rate, as indicated by their stacked X-ray flux. The similarity in average $K$, magnitude between galaxies with $2 \leq (z - K)_{AB} < 3$ and $(z - K)_{AB} \geq 3$ (Fig. 16) suggests they have similar masses, and the difference in $(z - K)_{AB}$ color between the two samples simply reflects the presence of some relatively unobscured star formation in those galaxies with $2 \leq (z - K)_{AB} < 3$.

4.2.2. Stellar Populations

Figure 18 further illustrates the differences between the star-forming and passively evolving galaxies in terms of some physical models. Figure 18a shows the $(z - K)_{AB}$ versus $(K - m_{3.6/4.5 \mu m})_{AB}$ colors (near-IR/IRAC color diagram) for all galaxies, excluding direct X-ray detections. Because the SEDs of (non-AGN) galaxies considered here are expected to be relatively flat in $f_{\nu}$ across the IRAC bands, we used 3.6 $\mu$m IRAC AB magnitudes for all sources that were not covered by the 4.5 $\mu$m imaging. Also shown in Figure 18a are synthetic colors for Bruzual & Charlot (2003) spectral templates at the mean redshifts of the BM ($z \sim 1.7$) and BX ($z \sim 2.2$) samples, assuming constant star formation, $E(B - V) = 0$ and 0.3, and a Calzetti et al. (2000) reddening law. The bulk of BX/BM and $BzK$/SF galaxies generally fall within the region of color space expected for constant star-forming galaxies with moderate extinction of $E(B - V) \sim 0.15$ and ages of $\sim 1$ Gyr. These values are consistent with those derived from detailed spectral modeling of BX/BM galaxies and LBGs by Shapley et al. (2005). Much of the scatter of star-forming galaxies to the left and right of the constant star formation models for $E(B - V) = 0.15 - 0.30$ is a result of photometric uncertainty, particularly in the $(K - m_{3.6/4.5 \mu m})_{AB}$ color, since we include galaxies with formal IRAC uncertainties of 0.5 mag. In addition, some of the scatter for objects with blue $(z - K)_{AB}$ colors arises from interlopers. The more interesting aspect of Figure 18a is that the constant star formation models cannot account for the colors of objects with $(z - K)_{AB} \gtrsim 3$: these objects must have ages less than the age of the universe at $z \sim 2$ ($\sim$ 3 Gyr) and simultaneously have modest $E(B - V)$—and hence modest current SFRs of $\lesssim 190 M_\odot$ yr$^{-1}$—such that they remain undetected as soft-band X-ray sources. The important result is that, similar to SED fitting, the X-ray stacking analysis allows us to rule out certain star formation histories. For the PE galaxies considered here, the X-ray data rule out the constant star formation models. The benefit of X-ray data is that we can quantify the current SFR independent of extinction and the degeneracies that plague SED fitting.

The only models that can account for the colors of objects with $(z - K)_{AB} \gtrsim 3$ are those with declining star formation histories (Fig. 18b). For example, DRG/PEs at $z \sim 2.2$ have colors that can be reproduced by dust-free models [$E(B - V) = 0.0$] with star formation decay timescales between $\tau = 10$ Myr (instantaneous burst) and $\tau \sim 700$ Myr. While the upper limit on the current average SFRs of DRG/PEs of $50 M_\odot$ yr$^{-1}$ (Fig. 16) does not help us further constrain the star formation history to a narrower range in $\tau$, the fact that DRG/PEs are still detected at $z$ band suggests that single stellar population models with small $\tau$ are unrealistic (e.g., ages greater than 1 Gyr imply $\gtrsim 100$ $e$-folding times for the instantaneous burst model, making such an object undetected at $z$ band). If there is ongoing low-level star formation activity, then a two-component model with an underlying old stellar population and a recent star formation episode may be required (e.g., Yan et al. 2004).

The red $(z - K)_{AB} > 3$ colors of $BzK$/PE galaxies can be reproduced by models with $\tau \sim 10 - 300$ Myr (for $\tau$ much larger

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Footnotes:

8 Labbé et al. (2005) propose a similar diagram to differentiate DRGs from other (e.g., star-forming) populations of $z \sim 2$ galaxies.

9 We rule out ages that are greater than the age of the universe at $z \sim 2.2$, giving an upper limit on the age of $\sim 3$ Gyr.
than 300 Myr, the models overpredict the current SFR). The X-ray data indicate that these BzK/PE galaxies have an average current SFR of \( \sim 28 \, M_\odot \, yr^{-1} \). For an age of 1 Gyr and \( \tau = 300 \, Myr \), this implies an “initial” SFR of \( \sim 800 \, M_\odot \, yr^{-1} \) at \( z = 2.4 \). This initial SFR is comparable to that of SMGs, and the implied formation redshift is close to the median redshift of SMGs (\( z \sim 2.2 \)), suggesting SMGs could be plausible progenitors of BzK/PE galaxies if the single-component model correctly described the star formation histories of these galaxies (e.g., Cimatti et al. 2004). The formation redshifts can be pushed back in time to significantly earlier epochs (\( z \approx 3.5 \)) if one assumes a more physically motivated “truncated” star formation history that models the effects of feedback in halting star formation. Nonetheless, the simplistic example above illustrates how X-ray estimates of the bolometric SFRs of galaxies can be combined with the results of stellar population modeling to indicate the likely progenitors of such galaxies. In summary, we have demonstrated the utility of stacked X-ray data as a powerful constraint on the results from stellar population modeling. The X-ray data indicate that galaxies with \( (z - K)_{AB} \gtrsim 3 \) have SEDs that are consistent with declining star formation history models. Other studies also show that the SEDs of BzK/PE galaxies can be adequately described by declining star formation history models (e.g., Daddi et al. 2005). The deep X-ray data confirm these results and further allow us to constrain the current SFRs of passively evolving and star-forming galaxies independent of the degeneracies associated with stellar population modeling.

### 4.2.3. Space Densities

To conclude this section, we note that objects selected by their \( J - K_s \) colors appear to include a substantial number of passively evolving galaxies at redshifts \( z \gtrsim 2 \) [although, as we pointed out above, the \( (z - K)_{AB} \) color may be a more effective means of determining which DRGs are passively evolving]. The space density implied by the four BzK/PE galaxies with \( (z - K)_{AB} > 3 \) and \( K_s < 21 \) is \( \sim 3 \times 10^{-5} \, Mpc^{-3} \), assuming a boxcar (or top-hat) selection function between redshifts \( 1.4 < z < 2.0 \) and an area of \( \sim 72.3 \) arcmin\(^2\). If we include all 17 BzK/PE galaxies [i.e., including those with \( (z - K)_{AB} < 3 \) and those four that are directly detected in X-rays] with \( K_s < 21 \), we find a space density of \( 1.3 \times 10^{-4} \, Mpc^{-3} \). Given the strong clustering observed for BzK/PE galaxies (e.g., Daddi et al. 2005), our estimate is in good agreement with the value of \( 1.8 \times 10^{-4} \, Mpc^{-3} \) obtained for the Daddi et al. (2005) sample of bona fide BzK/PE objects in the Hubble Ultra Deep Field (UDF), an area that is 6 times smaller than the area considered in our analysis (i.e., 12.2 arcmin\(^2\) in Daddi et al. 2005 vs. 72.3 arcmin\(^2\) considered here).

All of the BzK/PE galaxies would have been detected with \( K_s < 21 \) and \( (z - K)_{AB} > 3 \), assuming the PE model shown in Figure 18b, if they were at the mean redshift assumed for DRG/PEs of \( (z - K) = 2.2 \). The space density of the 13 DRG/PEs with \( (z - K)_{AB} > 3 \) is \( \sim 9 \times 10^{-5} \) to \( K_s = 21 \), assuming a boxcar selection function in the range \( 2.0 < z < 2.6 \) and an area of \( \sim 72.3 \) arcmin\(^2\). Here we have assumed that the range in redshifts of DRG/PEs \( 2.0 < z < 2.6 \) is similar to that of all DRG galaxies based on the spectroscopic redshift distribution shown in Figure 1. Our estimate of the DRG/PE space density is comparable to that obtained by Labbé et al. (2005) after restricting their sample to \( K_s < 21 \) (yielding one object over \( \sim 5 \) arcmin\(^2\)) and assuming a volume in the redshift range \( 2.0 < z < 2.6 \).

It is worth noting that the BzK/PE and DRG/PE populations appear to be highly clustered (e.g., Daddi et al. 2005; van Dokkum et al. 2004), and this will likely affect their density estimates over small volumes. While the space densities derived here are in rough agreement with other studies, our estimates have been derived over a much larger volume (by a factor of 6–14) than any previous study and will be less susceptible to variations in density due to clustering. We caution the reader that the density estimates may still be uncertain given that the redshift distribution of DRGs with \( z \gtrsim 2.6 \) is not well sampled, even in the large spectroscopic data set of DRGs considered here.

Taken at face value, the density estimates derived above suggest a significant presence of passively evolving \( K_s < 21 \) galaxies at redshifts \( z \gtrsim 2 \). This result contrasts with that of Daddi et al. (2005), who argue for a rapid decrease in the number density of passively evolving galaxies at redshifts \( z \gtrsim 2 \) based on BzK/PE selection. The drop-off in space density of passively evolving galaxies at redshifts \( z < 2 \), as suggested by Daddi et al. (2005), may be an artifact of the BzK/PE selection function, which, based on previously published redshift distributions and as shown in Figure 1, appears to miss passively evolving galaxies at redshifts \( z < 2 \), even when using the very deep B band of this study. Figure 12 shows that all of the DRGs that cluster around the BzK/PE selection window have limits in B band and that very few actually have limits that would for certain place them in the BzK/PE window. Photometric scatter for those galaxies with very faint (or no) B-band detections is likely to be significant for these galaxies. These results suggest that the depth of the B-band data is the determining factor in whether BzK/PE selection cuts galaxies with redshifts \( z \gtrsim 2 \) or not. Because the depth of the photometry is an issue for the BzK/PE selection, it becomes difficult to accurately quantify with a single selection criteria the drop-off in space density of passively evolving galaxies between \( z < 2 \) and \( z > 2 \).

We can avoid the need for excessively deep B-band data to select passively evolving galaxies with redshifts \( z \gtrsim 2 \) by simply selecting them using a single color, \( J - K_s \) or \( (z - K)_{AB} \). The stacked X-ray results show that a subsample of DRGs have very little star formation, suggesting that passively evolving galaxies have a significant presence at epochs earlier than \( z = 2 \). The inferred ages of DRGs would imply formation redshifts of \( z \sim 5 \) (Labbé et al. 2005).

We conclude this section by noting that there are several galaxies in the HS 1700+643 sample of Shapley et al. (2005), and many more in optically selected samples in general (e.g., D. K. Erb et al. 2005, in preparation), that have old ages and early formation redshifts similar to those of the passively evolving BzK/PE and DRG/PE galaxies discussed here. In order to reproduce the observed SEDs for such objects, the current SFR must be much smaller (but still detectable in the case of optically selected galaxies) than the past average SFR.

### 4.3. Selecting Massive Galaxies

As discussed above, DRGs with \( (z - K)_{AB} > 3 \) appear to be passively evolving based on their (lack of) stacked X-ray flux and their colors with respect to models with declining star formation histories. The X-ray data indicate that BzK/PE galaxies also appear to be well described by declining star formation histories, consistent with the SED modeling results of Daddi et al. (2005). The stellar mass estimates of these PE galaxies will be presented elsewhere. Here we simply mention that several existing studies of the stellar populations of BzK/PE and DRG galaxies with \( K_s < 20 \) indicate that they have masses \( \gtrsim \times 10^{11} \, M_\odot \) (e.g., Daddi et al. 2005; Förster Schreiber et al. 2004). In addition, Yan et al. (2004) recently analyzed the stellar populations of IRAC-selected extremely red objects (EROs), selected to have \( f_{3.6} \mu m / f_{5.8} \mu m \gtrsim 20 \) [or, equivalently, \( (z - 3.6 \mu m)_{AB} > 3.25 \)]. Spectral modeling indicates that these sources lie at redshifts
1.6 < z < 2.9, are relatively old (1.5–3.5 Gyr), and require an evolved stellar population to fit the observed SEDs. Almost all of the PE galaxies with (z − K)_{AB} > 3 satisfy the IERO criteria (shaded region of Fig. 18b). Furthermore, the R-band detections and limits for PEs with (z − K)_{AB} > 3 imply R − Ks ≥ 5.3, satisfying the ERO criteria.

The inferred stellar masses of the Shapley et al. (2005) sample of optically selected galaxies in the HS 1700+643 field are shown in Figure 19. For comparison, we also show the inferred stellar masses from the Yan et al. (2004) sample of IEROs.10 Both the Shapley et al. (2005) and Yan et al. (2004) samples take advantage of the longer wavelength IRAC data to constrain the stellar masses, and the typical uncertainty in mass is ~40% for objects with M* < 10^{11} M_\odot and ≤ 20% for objects with M* > 10^{11} M_\odot. The IERO stellar masses have been multiplied by 1.7 to convert from a Chabrier to Salpeter IMF. The scatter in stellar masses reflects at least a magnitude variation in the M/L ratio of BX/MD and IERO objects at a given rest-frame optical luminosity. [See the electronic edition of the Journal for a color version of this figure.]

10 H. Yan (2005), private communication.

[FIG. 19.—Inferred stellar masses of BX and “MD” objects from the Shapley et al. (2005) sample with spectroscopic redshifts 1.5 < z_{spec} < 2.9 (circles), and IEROs from the Yan et al. (2004) sample with photometric redshifts 1.6 < z_{phot} < 2.9 (squares; triangles for those with Ks-band limits). The stellar masses from Yan et al. (2004) have been multiplied by 1.7 to convert from a Chabrier to Salpeter IMF. The dashed vertical line denotes the limit brighter than which we are complete for IEROs [i.e., those DRGs with (z − K)_{AB} > 3]. A subset of BX galaxies have stellar masses similar to those of the IERO sample. The scatter in stellar masses reflects at least a magnitude variation in the M/L ratio of BX/MD and IERO objects at a given rest-frame optical luminosity. [See the electronic edition of the Journal for a color version of this figure.]

with (z − K)_{AB} > 3] have very little star formation. Therefore, a simple interpretation is that optical surveys include objects that are as massive (M* > 10^{11} M_\odot) as those selected in near-IR surveys, with the only requirement that the galaxies have some unobscured star formation. The range of SFRs (uncorrected for extinction) found for BX/BM galaxies is 3–60 M_\odot yr^{-1}, and it is likely that massive galaxies with at least a little unobscured star formation can be BX/BM selected. This may be the only significant difference between optical and near-IR selected massive galaxies, and the difference in SFR may be temporal. These criteria typically fail to select passively evolving galaxies at z ~ 2, as they have already settled to a quiescent stage. This does not mean that such massive galaxies will never appear in optical surveys. For example, a subsequent accretion event at z < 2 could elevate the star formation activity in an otherwise passively evolving massive galaxy, thus bringing it into the optical sample. Nonetheless, the DRG and BzK/PE criteria add to the census of galaxies at z ~ 2 by selecting passively evolving galaxies that have stellar masses similar to the most massive galaxies selected in the rest-frame UV.

4.4. Star Formation Rate Density at z ~ 2

4.4.1. Contribution from Optical and Near-IR Selected Samples

We can roughly estimate the contribution of BX/BM, BzK/SF, and DRG/SF galaxies to the extinction-free SFRD at z ~ 2.11 The BzK/SF criteria are designed to select galaxies with redshifts 1.4 < z < 2.6. The similarity in surface densities, volumes probed,

[FIG. 20.—Cumulative SFRD as a function of Ks magnitude for BX/BM (circles), BzK/SF (triangles), and DRG/SF (squares) galaxies with redshifts 1.4 < z < 2.6. The points are not independent of each other given the overlap between the samples. The shaded region denotes the total cumulative SFRD when counting overlap objects once. The total SFRD to Ks = 22 includes DRGs with Ks < 21. The error bars reflect the Poisson error and uncertainty in SFR added in quadrature, but do not reflect systematic errors associated with, e.g., photometric scattering. [See the electronic edition of the Journal for a color version of this figure.]

11 Although the BzK/PE galaxies do have detectable X-ray emission (e.g., Fig. 16), their contribution to the SFRD is minimal given that their space density is a factor of 5 smaller than that of the BzK/SF and BX/BM galaxies to Ks = 21 in the redshift range 1.4 < z < 2.0.]
TABLE 5
Cumulative Contributions to the Star Formation Rate Density in the Range 1.4 < \( z \) < 2.6

| Sample\(^a\) | \( z^b \) | \( \rho^c \) \( (\text{arcmin}^{-2}) \) | SFRD\(^d\) \( (M_\odot \text{ yr}^{-1} \text{ Mpc}^{-3}) \) |
|-------------|----------|-----------------|-----------------|
| BX/BM       | 1.4–2.6  | 0.44            | 0.016 ± 0.008   |
| BzK/SF      | 1.4–2.6  | 0.62            | 0.018 ± 0.004   |
| DRG/SF      | 2.0–2.6  | 0.15            | 0.008 ± 0.002   |
| BzK/SF – BX/BM | 1.4–2.6 | 0.35            | 0.007 ± 0.002   |
| DRG/SF – BzK/SF – BX/BM | 2.0–2.6 | 0.08          | 0.004 ± 0.001   |
| Total       | 2.0–2.6  | 0.87            | 0.027 ± 0.006   |

| Ks \( \leq 20.5 \) |
|-------------------|-----------------|-----------------|
| BX/BM             | 1.4–2.6  | 1.13            | 0.034 ± 0.009   |
| BzK/SF            | 1.4–2.6  | 1.35            | 0.032 ± 0.006   |
| DRG/SF            | 2.0–2.6  | 0.30            | 0.013 ± 0.003   |
| BzK/SF – BX/BM    | 1.4–2.6  | 0.55            | 0.012 ± 0.002   |
| DRG/SF – BzK/SF – BX/BM | 2.0–2.6 | 0.25          | 0.009 ± 0.002   |
| Total             | 2.0–2.6  | 1.93            | 0.055 ± 0.011   |

| Ks \( \leq 21.0 \) |
|-------------------|-----------------|-----------------|
| BX/BM             | 1.4–2.6  | 2.15            | 0.045 ± 0.010   |
| BzK/SF            | 1.4–2.6  | 2.34            | 0.044 ± 0.009   |
| DRG/SF            | 2.0–2.6  | 0.58            | 0.020 ± 0.004   |
| BzK/SF – BX/BM    | 1.4–2.6  | 0.74            | 0.014 ± 0.002   |
| DRG/SF – BzK/SF – BX/BM | 2.0–2.6 | 0.41          | 0.013 ± 0.002   |
| Total             | 2.0–2.6  | 3.30            | 0.072 ± 0.014   |

| Ks \( \leq 21.5 \) |
|-------------------|-----------------|-----------------|
| BX/BM             | 1.4–2.6  | 3.17            | 0.057 ± 0.013   |
| BzK/SF            | 1.4–2.6  | 3.61            | 0.052 ± 0.010   |
| BzK/SF – BX/BM    | 1.4–2.6  | 1.71            | 0.017 ± 0.002   |
| Total             | 2.0–2.6  | 5.29            | 0.087 ± 0.017   |

| Ks \( \leq 22.0 \) |
|-------------------|-----------------|-----------------|
| BX/BM             | 1.4–2.6  | 4.31            | 0.069 ± 0.015   |
| BzK/SF            | 1.4–2.6  | 4.93            | 0.068 ± 0.014   |
| BzK/SF – BX/BM    | 1.4–2.6  | 2.55            | 0.020 ± 0.003   |
| Total             | 2.0–2.6  | 7.27            | 0.102 ± 0.021   |

\( ^a \) The BzK/SF – BX/BM sample represents the set of objects that are BzK/SF selected but not BX/BM selected. Similarly, the DRG/SF – BzK/SF – BX/BM sample represents the set of DRGs that are not selected by either the BzK/SF or BX/BM criteria.

\( ^b \) Redshift range of sample.

\( ^c \) Surface density of photometric objects after removing interlopers and directly detected X-ray sources that are likely AGNs. The number of BX/BM objects is calculated assuming the spectroscopic and interloper fractions from Table 3. The overlap fractions are taken from Fig. 10. We assume a field area of \( \sim 72.3 \text{ arcmin}^2 \) to compute surface densities.

\( ^d \) Assumes the average SFRs shown in Fig. 15.

\( ^e \) This includes the contribution from the DRG/SF – BzK/SF – BX/BM sample for \( K_s < 21 \).

and SFRs of galaxies in the BzK/SF and BX/BM samples implies that their contribution to the SFRD will be comparable for objects with \( K_s < 22 \). The redshift distribution of \( K_s < 21 \) DRGs from within our own sample is reasonably well defined over this redshift range (see Fig. 1), so we can estimate the added contribution of \( \sim 80\% \) of the DRGs with redshifts 2.0 \( \leq z < 2.6 \) to the SFRD between redshifts 1.4 \( < z < 2.6 \). Figure 20 and Table 5 show the cumulative contribution to the SFRD of BzK/SF, BX/BM, and DRG/SF galaxies. The points in Figure 20 are not independent of each other due to the overlap between the samples (e.g., Fig. 10). Also shown in Figure 20 by the shaded region is the inferred total SFRD assuming the overlap fractions of Figure 10 and counting all objects once. The results indicate that BX/BM selection would miss approximately one-third of the total SFRD from BX/BM and BzK/SF galaxies to \( K_s = 22 \) and DRG/SF \( K_s < 21 \) galaxies combined. We remind the reader that much of the incompleteness of the BX/BM sample with respect to that of the BzK/SF sample (and vice versa) results from photometric scattering (e.g., Figs. 11 and 12). Monte Carlo simulations can be used to quantify the biases of such photometric inaccuracy and thus correct for incompleteness (e.g., Reddy et al. 2005). The total SFRD in the interval 1.4 \( < z < 2.6 \) for BX/BM and BzK/SF galaxies to \( K_s = 22 \) and DRG/SF galaxies to \( K_s = 21 \), taking into account the overlap between the samples, is \( \sim 0.10 \pm 0.02 \text{ M}_\odot \text{ yr}^{-1} \text{ Mpc}^{-3} \). Approximately 30\% of this comes from galaxies with \( K_s < 20 \) (Table 5). Optically selected galaxies to \( R = 25.5 \)
and \( K_r = 22.0 \) and \( BzK/SF \) galaxies to \( K_r = 22.0 \) (with significant overlap between the two samples) account for \( \sim 87\% \) of the total SFRD quoted above. DRGs to \( K_r = 21 \) that are not selected by the BX/BM or \( BzK/SF \) criteria contribute the remaining \( \sim 13\% \). We note that the number \( \sim 0.10 \pm 0.02 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \) does not include the five radio-selected SMGs to \( S_{850 \mu m} \approx 5 \, \text{mJy} \) that are near-IR and/or optically selected since we removed most of the directly detected X-ray sources in computing the SFRD. If we add these five radio-selected SMGs that are present in the optical and near-IR samples (all of which have \( K_r < 21 \)), then the total SFRD contributed by the BX/BM and \( BzK/SF \) objects to \( K_r = 22.0 \) and DRG/SF galaxies to \( K_r = 21.0 \) is \( \sim 0.15 \pm 0.03 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \) (see next section).

### 4.4.2. Contribution from Submillimeter Galaxies

We conclude this section by briefly considering the contribution of radio-selected SMGs with \( S_{850 \mu m} \approx 5 \, \text{mJy} \) to the SFRD. All but one of the radio-selected SMGs summarized in Table 4 are directly detected in either the soft or hard band and are likely associated with AGNs. Stacking the X-ray emission for the five radio-selected SMGs with redshifts \( 1.4 < z < 2.6 \) in Table 4 yields an average inferred SFR of \( \sim 2900 \, M_\odot \, \text{yr}^{-1} \), and this value should be regarded as an upper limit given that the X-ray emission is likely contaminated by AGN. On the other hand, the average bolometric luminosity of the five SMGs, as derived from their submillimeter flux, is \( \langle L_{bol} \rangle \sim 9 \times 10^{12} \, L_\odot \). If we assume that 30\% of \( L_{bol} \) arises from AGNs (e.g., Chapman et al. 2005; Alexander et al. 2005), then the implied SFR is \( \sim 1000 \, M_\odot \, \text{yr}^{-1} \). If we take at face value the assertion that 30\% of the bolometric luminosity of SMGs comes from AGNs, then this means that the X-ray emission would overestimate the average SFR of SMGs by a factor of \( \sim 3 \). In other words, only one-third of the X-ray emission from SMGs would result from star formation, and the remaining two-thirds would come from AGNs.

To determine the additional SFRD provided by radio-selected SMGs with \( S_{850 \mu m} \approx 5 \, \text{mJy} \), we must account for their overlap with the optical and near-IR samples. The data in Table 4 show that there are four of nine SMGs that are not selected by the optical and/or near-IR criteria. All four of these galaxies have relatively low redshifts \( z \approx 1 \) and will obviously not contribute to the SFRD between redshifts \( 1.4 < z < 2.6 \). Alternatively, of the five SMGs that are spectroscopically confirmed to lie at redshifts \( 1.4 < z < 2.6 \), all are selected by either the BX/BM, \( BzK/SF \), or DRG criteria (and sometimes by more than one set of criteria).

Because of the nonuniform coverage of the submillimeter observations, we must rely on the published submillimeter number counts to estimate the effective surface density probed by the nine radio-selected SMGs with \( S_{850 \mu m} \approx 5 \, \text{mJy} \) listed in Table 4. According to the models shown in Figure 4 of Smail et al. (2002), we should expect to find \( \sim 0.25 \) sources arcmin\(^{-2}\) to \( S_{850 \mu m} \approx 5 \, \text{mJy} \). Neglecting cosmic variance, the nine observed radio-selected SMGs to \( S_{850 \mu m} \approx 5 \, \text{mJy} \) then imply an effective surface area of \( \sim 36 \, \text{arcmin}^2 \). The spectroscopic redshifts compiled in Table 2 of Chapman et al. (2005) indicate that \( \sim 44\% \) of the radio-selected SMGs to \( S_{850 \mu m} \approx 5 \, \text{mJy} \) lie at redshifts outside the range \( 1.4 < z < 2.6 \). If we assume a Poisson distribution of sources, then the total number of SMGs to \( S_{850 \mu m} \approx 5 \, \text{mJy} \) could be as high as \( 9 + \sqrt{9} = 12 \). If we assume that the fraction of interlopers among the three unobserved objects is similar to the fraction of interlopers among objects that are observed, then we expect an upper limit of two SMGs with \( S_{850 \mu m} \approx 5 \, \text{mJy} \) that are unobserved and that lie in the redshift range \( 1.4 < z < 2.6 \). If we conservatively assume that these two sources are not selected by the optical and/or near-IR criteria and that they have bolometric SFRs of \( \sim 1500 \, M_\odot \, \text{yr}^{-1} \) (similar to the average SFR found for the five spectroscopically confirmed radio-selected SMGs in Table 4), then the inferred additional SFRD provided by these two SMGs would be \( \sim 3000 \, M_\odot \, \text{yr}^{-1} \) divided by the volume subtended by \( 36 \, \text{arcmin}^2 \) at redshifts \( 1.4 < z < 2.6 \), or \( \sim 0.022 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \). We note that this should be treated as an upper limit for several reasons. First, we have assumed the maximum number of unobserved sources allowed by Poisson statistics. Second, we have assumed an interloper fraction among these unobserved sources that is the same for the observed sources. In general, one might expect the contamination fraction to be higher among the general SMG population to \( S_{850 \mu m} \approx 5 \, \text{mJy} \) (where an accurate radio position may not be known) than would be inferred from the radio-selected SMG surveys. Finally, we have assumed that all of the unobserved sources cannot be selected by their optical and/or near-IR colors. Neglecting any overlap, radio-selected SMGs to \( S_{850 \mu m} \approx 5 \, \text{mJy} \) contribute \( \sim 0.05 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \) to the SFRD in the range \( 1.4 < z < 2.6 \). However, our conservative calculation indicates that radio-selected SMGs to \( S_{850 \mu m} \approx 5 \, \text{mJy} \) that are not selected by optical (BX/BM) and/or near-IR (\( BzK \) and/or DRG) surveys make a small (\( \leq 0.022 \, M_\odot \, \text{yr}^{-1} \, \text{Mpc}^{-3} \) or \( \leq 15\% \) additional contribution to the SFRD in the range \( 1.4 < z < 2.6 \).

### 5. CONCLUSIONS

We have taken advantage of the extensive multiwavelength data in the GOODS-North field to select galaxies at \( z \approx 2 \) based on their optical and near-IR colors and to compare them in a consistent manner. Our own ground-based optical and near-IR images are used to select galaxies based on their \( U_r/GR \), \( BzK \), and \( J - K \) colors. Additional rest-frame UV spectroscopy for 25\% of optically selected candidates allows us to quantify the redshift selection functions for the various samples. We use the deep \textit{Chandra} 2 Ms X-ray data to determine the influence of AGNs and estimate bolometric SFRs for galaxies in the optical and near-IR samples. We also use the deep \textit{Spitzer} IRAC data in the GOODS-N field in considering the stellar populations and masses of galaxies selected in different samples. Our analysis employs the same multiwavelength data for a single field (GOODS-N), using the same photometric measurement techniques, for a consistent comparison between galaxies selected by their optical and near-IR colors. Our main conclusions are as follows:

1. Star-forming galaxies at \( z \approx 2 \) selected by their \( U_r/GR \) colors (i.e., BX/BM galaxies) and their \( BzK \) colors (i.e., \( BzK/SF \) galaxies) have optical and near-IR color distributions that indicate significant overlap (\( \sim 70\% - 80\% \)) between the two samples. Photometric scatter could account for the colors of at least half of those galaxies missed by one set of criteria or the other. The \( BzK/SF \) criteria are less efficient in selecting (younger) \( K_r > 21 \) galaxies at redshifts \( 1.4 < z < 2.6 \), while the BX/BM criteria are less efficient in selecting near-IR bright (e.g., \( K_r < 20 \)) objects. Distant red galaxies (DRGs; including both reddened star-forming and passively evolving galaxies) selected to have \( J - K_0 > 2.3 \) show near-IR colors that are \( 1 - 1.5 \) mag redder than for samples of star-forming galaxies. Criteria aimed at selecting passively evolving galaxies based on their \( BzK \) colors (i.e., \( BzK/PE \) galaxies) by design have red near-IR colors, but we find that the redshift distributions of \( BzK/PE \) galaxies and DRGs have very little overlap.

2. The deep X-ray data show that almost all of the directly detected X-ray sources in the samples have hard-band emission and X-ray/optical flux ratios indicating they are likely AGNs. Much of this AGN contamination occurs for magnitudes \( K_r < 20 \).
identify five objects that are detected in the soft-band X-ray data and are likely star-forming galaxies based on their absence in the hard-band X-ray data, optical magnitudes \( R > 22 \), and absence of obvious AGN features for those with spectra. We stacked the X-ray data for all likely star-forming galaxies (i.e., those undetected in X-rays and the five galaxies discussed above), excluding likely AGNs. The stacking analysis shows that the SFR distributions of BX/BM and \( BzK/SF \) galaxies and DRGs are very similar as a function of \( K_s \) magnitude. Galaxies with \( K_s < 20 \) have average SFRs of \( ~120 \) \( M_\odot \) yr\(^{-1} \), a factor of 2–3 higher than \( K_s > 20.5 \) galaxies. Previous studies point to a similarity in the metallicities, clustering, and stellar masses of \( K_s < 20 \) optical and near-IR selected galaxies (e.g., Shapley et al. 2004; Adelberger et al. 2005). In this work we show that the bolometric SFRs of optical and near-IR selected galaxies are also very similar when subjected to a common near-IR magnitude.

3. Near-IR selection of star-forming galaxies should be more immune to the effects of dust obscuration than optical surveys. However, the BX/BM, \( BzK/SF \), and DRG samples show very similar SFRs as a function of near-IR color for galaxies with \( (z - K)_{AB} < 3 \). The SFRs inferred for \( BzK/SF \) galaxies that are not optically selected are very similar to \( BzK/SF \) galaxies that do satisfy the optical criteria, suggesting that star-forming galaxies in near-IR samples that are missed by optical criteria do not harbor large numbers of heavily reddened galaxies. Furthermore, the optical and \( BzK/SF \) samples host an approximately equal number of SMGs.

4. We identify a population of extremely red \( BzK \) and DRG galaxies with \( (z - K)_{AB} \geq 3 \). The stacked X-ray data indicate that these red galaxies have little, if any, current star formation. The absence of X-ray emission from these objects also suggests that low-luminosity AGNs and low-mass X-ray binaries contribute little X-ray emission in star-forming galaxies compared with the emission produced from more direct tracers of the current SFR, such as high-mass X-ray binaries. We further demonstrate the utility of deep X-ray data to constrain the stellar populations of these extremely red galaxies and find that they must be described by declining star formation histories. Almost all of these passively evolving galaxies satisfy the IERO criteria of Yan et al. (2004). We find that optical selection includes a subset of galaxies with stellar masses similar to those inferred for IEROs, but which are forming stars at a prodigious rate. The stellar mass estimates from SED modeling (e.g., Yan et al. 2004; Förster Schreiber et al. 2004) and bolometric SFR estimates from the deep X-ray data (this work) suggest that the presence or absence of star formation may be the only significant difference between optical and near-IR selected massive galaxies (\( M^* > 10^{11} M_\odot \)), and the difference in SFR may be temporal.

5. We find evidence for a significant presence of passively evolving galaxies at redshifts \( z \geq 2 \) compared to their space density at lower redshifts, \( 1.4 < z < 2.0 \). Our analysis suggests that a single-color technique using the \( (z - K)_{AB} \) or \( J - K_s \) color allows for a more practical method of selecting passively evolving galaxies with \( z \approx 2 \) than the \( BzK/PE \) criteria, as the latter would require excessively deep B-band data to accurately determine the space densities of passively evolving galaxies at \( z \geq 2 \).

6. Finally, we consider the contribution of optical and near-IR selected galaxies to the SFRD at \( z \sim 2 \), taking into account the overlap between the samples and their respective redshift distributions. We find that BX/BM and \( BzK/SF \) galaxies to \( K_s = 22 \) and DRG galaxies to \( K_s = 21 \) account for an SFRD of \( \sim 0.10 \pm 0.02 \) \( M_\odot \) yr\(^{-1} \) Mpc\(^{-3} \) in the redshift range \( 1.4 < z < 2.6 \). Approximately 87% of this total comes from optically selected galaxies to \( R = 25.5 \) and \( K_s = 22 \) and near-IR selected \( BzK \) galaxies to \( K_s = 22 \), and 13% from \( K_s < 21 \) DRGs not selected by the BX/BM or \( BzK \) criteria. Of the known radio-selected SMGs to \( S_{850,\mu m} \sim 4 \) mJy in the GOODS-N field with redshifts \( 1.4 < z < 2.6 \), \( \approx 80\% \) could be selected by the BX/BM, \( BzK \), and/or DRG criteria.

We thank Scott Chapman for discussions regarding submillimeter galaxies in the GOODS-North field. Haojing Yan kindly provided stellar mass estimates for IEROs. We thank David Alexander for his suggestions regarding the use of the X-ray data, and Amy Barger for her comments regarding Table 4. N. A. R., D. K. E., and C. C. S. are supported by grant AST 03-07263 from the National Science Foundation and by the David and Lucile Packard Foundation. A. E. S. and K. L. A. are supported by the Miller Foundation and the Carnegie Institute of Washington, respectively.

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