FIREWORKS $U_{38}$-to-24 μm PHOTOMETRY OF THE GOODS-CDFS: MULTI-WAVELENGTH CATALOG AND TOTAL IR PROPERTIES OF DISTANT $K_s$-SELECTED GALAXIES

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\textit{Draft version November 1, 2018}

Abstract

We present a $K_s$-selected catalog, dubbed FIREWORKS, for the Chandra Deep Field South (CDFS) containing photometry in $U_{38}$, $B_{435}$, $B$, $V$, $V_{606}$, $R$, $i_{775}$, $I$, $z_{850}$, $J$, $H$, $K_s$, $[3.6\mu m]$, $[4.5\mu m]$, $[5.8\mu m]$, $[8.0\mu m]$, and the MIPS $[24\mu m]$ band. The imaging has a typical $K_{s,AB}^{\text{tot}}$ limit of 24.3 mag (5σ) and coverage over 113 arcmin$^2$ in all bands and 138 arcmin$^2$ in all bands but $H$. We cross-correlate our catalog with the 1 Ms X-ray catalog by Giacconi et al. (2002) and with all available spectroscopic redshifts to date. We find and explain systematic differences in a comparison with the $1^\prime z_{850} + K_s$-selected GOODS-MUSIC catalog that covers ∼90% of the field. We exploit the $U_{38}$-to-24 μm photometry to determine which $K_s$-selected galaxies at $1.5 < z < 2.5$ have the brightest total IR luminosities and which galaxies contribute most to the integrated total IR emission. The answer to both questions is that red galaxies are dominating in the IR. This is true no matter whether color is defined in the rest-frame UV, optical, or optical-to-NIR. We do find however that among the reddest galaxies in the rest-frame optical, there is a population of sources with only little mid-IR emission, suggesting a quiescent nature.

Subject headings: galaxies: distances and redshifts - galaxies: high redshift - infrared: galaxies

1. INTRODUCTION

Since the original Hubble Deep Field (Williams et al. 1996), deep multi-wavelength observations of blank fields have revolutionized our understanding of the high-redshift universe. Especially the epoch around $z \sim 2$ is of great interest since it is then that the cosmic star formation rate density was peaking (Hopkins & Beacom 2006). At $z \sim 2$, the observed optical probes the redshifted rest-frame UV emission, making it a good tracer for relatively unobscured star formation. Near-Infrared (NIR) observations of distant galaxies, such as undertaken by the FIRE surveys in the Hubble Deep Field South (HDFS, Labb\textsuperscript{e} et al. 2003, hereafter L03) and the MS1054–03 field (Förster Schreiber et al. 2006, hereafter FS06), show relatively small variations in the rest-frame $V$-band mass-to-light ratio. Selecting galaxies in the $K_s$-band (e.g., L03; FS06) thus provides a good probe of the massive galaxy content at high redshift.

In the presence of dust, large amounts of rest-frame UV emission can be absorbed and re-emitted in the Far-Infrared (FIR). Dust corrections of the UV luminosities of such systems involve large uncertainties. Direct observations of the dust emission are therefore crucial to get a better census of the bolometric energy output. In order to study the bolometric properties of typical galaxies at $z \sim 2$, infrared luminosities have been derived from the observed 24 μm flux by means of IR spectral energy distribution (SED) templates (e.g., Papovich et al. 2005; Reddy et al. 2006).

Despite the extra model uncertainty involved, this approach adds complementary information to the shorter wavelength studies of high-redshift galaxies. While the Luminous ($10^{11} L_\odot < L_{IR} < 10^{12} L_\odot$) and Ultraluminous ($L_{IR} > 10^{12} L_\odot$) Infrared Galaxies, (U)LIRGS (Sanders & Mirabel 1996) are locally very rare, they are found to be increasingly more common toward higher redshifts (e.g., Caputi et al. 2006).

In this paper, we present a $K_s$-band selected multi-wavelength catalog for the GOODS-CDFS, comprising WFI $U_{38}$ BVRI, ACS $B_{435} V_{606} i_{775} z_{850}$, ISAAC JHK$\_s$, IRAC 3.6-8.0 μm and MIPS 24 μm imaging. We adopt a similar format as for the publicly available FIRE catalogs of the HDFS and MS1054–03, hence the name FIREWORKS. This allows the user to exploit the combined photometry of the CDFS, MS1054–03, and the HDFS in a straightforward manner. The fields are complementary in depth (5σ for point sources $K^\text{tot}_{s,AB} = 24.3, K^\text{tot}_{s,AB} = 25.0, K^\text{tot}_{s,AB} = 25.6$ respetively) and area (138 arcmin$^2$, 24 arcmin$^2$, and 5 arcmin$^2$ respectively).

An analysis of the space density and colors of massive galaxies at $2 < z < 3$ (van Dokkum et al. 2006), the rest-frame optical luminosity density and stellar mass density up to $z \sim 3$ (Rudnick et al. 2006), and the rest-frame luminosity functions of galaxies at $2 < z < 3.5$ (Marchesini et al. 2006) were partly based on the FIREWORKS catalog for the GOODS-CDFS presented here.

After describing the catalog construction, we particularly address the questions which $K_s$-selected galaxies at $1.5 < z < 2.5$ are brightest at 24 μm, which galaxies have the largest total infrared luminosity $L_{IR}$ ($\equiv L(8-1000 \mu m)$) and contribute most to the total integrated IR luminosity emitted by $K_s$-selected galaxies.
We address this question by studying the IR emission as function of color defined in three wavelength regimes: the rest-frame UV, optical, and optical-to-NIR.

An overview of the observations is presented in §2. §3 describes the construction of the final mosaics. Source detection and photometry is discussed in §4. Next, we present our photometric redshifts (z$_{\text{phot}}$) and cross-correlation with the available spectroscopic surveys in §5. §6 summarizes the catalog content. A photometric comparison for the wavelength bands in common with the GOODS-MUSIC catalog by Grazian et al. (2006a, hereafter G06a) and a z$_{\text{phot}}$ comparison with the same authors is discussed in §7. Results on 24 $\mu$m properties and total infrared luminosities of K$_s$-selected galaxies at $1.5 < z < 2.5$ are discussed in §8. §9 summarizes the paper.

AB magnitudes are used throughout this paper. We adopt a $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ cosmology.

2. OBSERVATIONS

2.1. The GOODS Chandra Deep Field South

Centered on $(\alpha, \delta) = (03:32:30, -27:48:30)$, the CDFS (Giacconi et al. 2000) has been targeted by most of today's major telescope facilities, both in imaging mode over the whole spectral range and in spectroscopic mode. Among the surveys carried out in areas included in the CDFS are K20 (Cimatti et al. 2002), GMASS (Cimatti et al. in preparation), VVDS (Le Fèvre et al. 2004), and the Hubble Ultra Deep Field (Beckwith et al. 2006). In this section, we describe the public GOODS-South dataset that we used to build a K$_s$-band selected catalog containing homogeneous colors from the optical to 24 $\mu$m.

2.2. The WFI $U_{38}$BVRI data

Ground-based optical imaging of the Extended CDFS with the Wide Field Imager (WFI) on the ESO/MPG 2.2m telescope was obtained as part of the COMBO-17 (Wolf et al. 2004) and ESO DPS (Arnouts et al. 2001) surveys. We use the central part of the WFI $U_{38}$, B, V, R, and I imaging, where it overlaps with the GOODS K$_s$-band imaging, that has been re-reduced by the GaBoDS consortium (Erben et al. 2005; Hildebrandt et al. 2006). The images were released on a 0′′.238 pixel$^{-1}$ scale and have exposure times of 49, 69, 105, 88, and 35 ks in $U_{38}$, B, V, R, and I respectively.

2.3. The ACS B$_{435}$V$_{606}$i$_{775}$z$_{850}$ data

During 5 epochs of observations, the ACS camera on HST acquired imaging of the GOODS-South field in 4 filter bands: F435W, F606W, F775W, and F850LP (hereafter referred to as B$_{435}$, V$_{606}$, i$_{775}$, and z$_{850}$). Exposure times amounted to 2, 1.7, 1.7, and 3.3 hours respectively. The mosaics (version v1.0; Giavalisco et al. 2004), were drizzled onto a pixel scale of 0′′.03 pixel$^{-1}$. From the 150 arcmin$^2$ area that is well covered by the K$_s$-band detection image, 138 arcmin$^2$ is well exposed with ACS. We restrict our analysis of the total IR properties of the distant galaxy population in §8 to this overlap region.

2.4. The ISAAC JHK$_s$ data

We use the ESO/Goods data release v1.5 (http://www.eso.org/science/goods/releases/20050930/) to complement the optical observations with NIR imaging by the Very Large Telescope (VLT). For a full description of the dataset, we refer to Vandame et al. (in preparation). Briefly, the v1.5 data release consists of 24 fully reduced VLT/ISAAC fields in the J and K$_s$ bands and 19 fields in the H-band, each with a 2.5′ x 2.5′ FOV and 0′′.15 pixel$^{-1}$ scale. The ISAAC data were reduced using the ESO/MVM image processing pipeline (v1.9, see Vandame 2002 for the description of an earlier version). Exposure times varied from field to field, with typical exposures of 3.2, 4.2, and 5 hours in J, H, and K$_s$-band respectively, and respective ranges between ISAAC fields of 2-5 hours, 2-6 hours, and 3.6-7.5 hours. The variations in depth resulting from the unequal exposure times are discussed in §3.5. A total area of 113 arcmin$^2$ is well exposed in all optical and NIR filter bands. Without a restriction on the H-band, the covered area increases to 138 arcmin$^2$.

2.5. The IRAC 3.6-8.0 $\mu$m data

As a Spitzer Space Telescope Legacy Program, superdeep images of the GOODS-South field were taken with the Infrared Array Camera (IRAC, Fazio et al. 2004) on-board Spitzer. Over 2 epochs the whole field was covered in the 3.6 $\mu$m, 4.5 $\mu$m, 5.8 $\mu$m, and 8.0 $\mu$m bands. For each epoch, exposure times per channel per sky pointing amounted to 23 hours. With the telescope orientation being rotated by 180 degrees between the two epochs, the second epoch IRAC channel 1 and 3 observations targeted the area covered by IRAC channel 2 and 4 during the first epoch, and vice versa. An overlap region of roughly 40 arcmin$^2$, including the Hubble Ultra Deep Field (Beckwith et al. 2003), got twice the exposure time. We use the data releases DR2 and DR3 for the second and first epoch respectively. Images were released on a 0′′.60 pixel$^{-1}$ scale. A full description of the observations and reduction will be presented by Dickinson et al. (in preparation).

2.6. The MIPS 24 $\mu$m data

The GOODS-South field was observed at 24 $\mu$m with the Multiband Imaging Photometry for Spitzer (MIPS, Rieke et al. 2004) on-board Spitzer, closely overlapping the IRAC fields with a position angle that is rotated with respect to the IRAC observations by approximately 3 degrees. The MIPS campaign led to a nearly uniform exposure time of 10 hours. We use the version v0.30 reduced images, released on a 1′′.20 pixel$^{-1}$ scale, based on the Spitzer Science Center (SSC) Basic Calibrated Data (BCD) pipeline (version S11.0.2).

3. FINAL IMAGES

In this section, we describe the image quality of the publicly released data products, the subsequent steps undertaken to obtain the final mosaics from which the photometric catalog is extracted, and the limiting depths reached at all wavelengths. The main characteristics of the multi-wavelength data set are summarized in Table 1.

3.1. Pixel scales and large scale backgrounds
First, we converted the ACS images to the 0′/15 pixel−1 scale of the $K_s$-band detection image by 5 × 5 pixel block averaging with flux conservation. All space-based optical and NIR photometry was performed on this pixel scale using the SExtractor software version 2.2.2 (Bertin &Arnouts 1996) (see §4).

A source fitting algorithm developed by Labb´e et al. (in preparation), especially suited for heavily confused images for which a higher resolution prior (in this case the $K_s$-band image) is available, was used to extract photometry from the WFI, IRAC and MIPS images (see §4.2.0). The WFI images were registered to the $K_s$-band mosaic with a 0′/15 pixel−1 scale using position measurements of stars and compact objects and the IRAF geotran tasks. For the MIR photometry, the algorithm requires a higher resolution image than provided by the IRAC and MIPS images. However, the native $K_s$-band pixel scale makes it more computationally expensive without benefit in accuracy. A 2 × 2 block averaged version of the $K_s$-band mosaic was therefore produced with a 0′/3 pixel−1 scale. We registered the publicly released IRAC and MIPS images onto this $K_s$-band image using the WCS information in the image header in combination with a minor additional shift based on position measurements of stars and compact sources, again forcing flux conservation. We note that the source fitting algorithm takes care of residual shifts. Since the programme does not take into account large scale background variations, these were removed a priori from the IRAC and MIPS images by subtracting SExtractor background images produced with large background mesh settings (BACK_SIZE=64, BACK_FILTERSIZE=3 on a 0′/3 pixel−1 scale). The subtracted background varied over the image by -2 to 0 times the rms noise.

### 3.2. Image quality and PSF matching

#### Space-based optical and NIR wavelengths

In order to obtain consistent color measurements, we match all space-based optical and NIR images to a common resolution, namely that of the field with the broadest point spread function (PSF). Since the ground-based optical, IRAC, and MIPS images have a significantly broader PSF, they are not included in the simple PSF matching, but are treated separately by a source-fitting algorithm (see §4.2.0). In this section, we describe the selection of stars used to build the PSFs, the construction of the PSFs for the ACS $B_{435}$-, $V_{606}$-, $i_{775}$-, and $z_{850}$-mosaics and for each of the ISAAC fields in the $J$-, $H$-, and $K_s$-band, the construction of the convolving kernels, and the quality of the PSF matching.

First, we compiled a list of bright, isolated, unsaturated stars. Initially, well-exposed objects with $(J - K_s)_{AB} < 0.04$ and $K_{tot} < 22.86$ mag were selected from a preliminary catalog of the CDFS. For ISAAC fields where the number of $J - K_s$ selected stars was low, we complemented the sample with stars from the EIS stellar catalog (Groenewegen et al. 2002). During a first iteration, the list was cleaned from galaxy-like objects, stars

| Camera | Filter | $\lambda_c$ (Å) | FWHM (arcsec) | $3\sigma$ Total Limiting Magnitude (AB mag) |
|--------|--------|----------------|---------------|-----------------------------------------|
| WFI $U_{38}$ | 3656 | 0.93 | 26.06 |
| WFI $B$ | 4601 | 0.97 | 27.21 |
| WFI $V$ | 5379 | 0.90 | 26.88 |
| WFI $R$ | 6516 | 0.78 | 26.99 |
| WFI $I$ | 8658 | 0.93 | 25.00 |

| Camera | Filter | $\lambda_c$ (Å) | FWHM (arcsec) | $3\sigma$ Total Limiting Magnitude (AB mag) |
|--------|--------|----------------|---------------|-----------------------------------------|
| ACS $B_{435}$ | 4327 | 0.22 | 27.68 |
| ACS $V_{606}$ | 5957 | 0.22 | 27.81 |
| ACS $i_{775}$ | 7705 | 0.21 | 27.26 |
| ACS $z_{850}$ | 9072 | 0.22 | 26.90 |

| Camera | Filter | $\lambda_c$ (Å) | FWHM (arcsec) | $3\sigma$ Total Limiting Magnitude (AB mag) |
|--------|--------|----------------|---------------|-----------------------------------------|
| ISAAC $J$ | 12379 | 0.38 - 0.61 | 25.82 - 26.42 |
| ISAAC $H$ | 16517 | 0.35 - 0.65 | 25.39 - 25.95 |
| ISAAC $K_s$ | 21681 | 0.38 - 0.58 | 25.02 - 25.96 |

| Camera | Filter | $\lambda_c$ (Å) | FWHM (arcsec) | $3\sigma$ Total Limiting Magnitude (AB mag) |
|--------|--------|----------------|---------------|-----------------------------------------|
| IRAC ch1 | 35634 | 1.6 | 26.15 |
| IRAC ch2 | 45110 | 1.7 | 25.66 |
| IRAC ch3 | 57593 | 1.9 | 23.79 |
| IRAC ch4 | 79559 | 2.0 | 23.70 |
| MIPS 24 µm | 237000 | 6.0 | 21.30 |

The intrinsic ACS PSF has a FWHM of 0′/12. The values quoted in this table were measured on the 5 × 5 block averaged mosaics. The ACS photometry was performed on the images convolved to the broadest NIR PSF.
The seeing FWHM of the NIR ISAAC observations varied from 0.35 to 0.65, with median values of 0.47, 0.48, and 0.47 in $J$, $H$, and $K_s$ respectively. The values of the Moffat $\beta$ parameter were 3.1, 2.9, and 3.0 in $J$, $H$, and $K_s$. Fig. 1 illustrates the distribution of FWHMs of the natural PSFs for the individual ISAAC fields. In all of the considered bands and fields, the FWHM of the individual stars were within $\approx$0.10% of that measured on the final average PSF of the image. We adopted the 0.65 $H$-band PSF of ISAAC field f15 as target to which all higher resolution images were matched.

We computed the kernel for convolution for each ISAAC field and band separately, using the Lucy-Richardson deconvolution algorithm. The kernels are well represented by a Moffat profile with $\beta$ parameters varying from field to field and band to band. The ratio of the growth curve of the convolved PSF over that of the target PSF is a good measure for the PSF matching accuracy. Overall, the ratio of growth curves deviated by at most 5.1% from unity for apertures between 1" ($\approx$1.5 FWHM of the PSF of the smoothed field maps) and 6" (the reference aperture for photometric calibration), with an average of 0.54% $\pm$ 0.90%. Flux within 3" radius is well conserved during the convolution process, with a median deviation of 0.06% and a median absolute deviation of 0.6%.

The construction of convolving kernels for the ACS mosaics required an extra step. The kernels obtained from deconvolution with the IRAF Lucy task had significant noise in the outer parts, leading to noise spikes around bright point-like sources in the convolved ACS mosaics. To remove these artifacts, we modeled the ACS-to-ISAAC kernels by fitting isophotes using the IRAF tasks ellipse and bmodel, and used the modeled kernels for the convolution. This is possible because the kernels are otherwise well behaved and very azimuthally symmetric. The ACS-to-ISAAC kernels have a nearly Moffat profile with a $\beta$ parameter of 3.

Because of the different basic shapes of the ACS and ISAAC PSFs, an excellent matching over the relevant radii is more difficult than in general among ISAAC fields. Nevertheless, the offsets of the growth curve ratios between 1" and 6" are limited to below 4.7%, with an average of 1.58% $\pm$ 1.32%. The average over all stars of the ratio of the flux measured within 3" radius in the convolved and that measured in the natural image showed a flux conserving accuracy of 0.7% or better for all ACS bands.

**Ground-based optical and MIR wavelengths**

The seeing PSF of the WFI observations is significantly broader than that of our $K_s$-band detection image ($\approx$0.9" FWHM). The FWHM measured on the average image of bright, isolated stars in the IRAC images even amounts to 1.6", 1.7", 1.9", and 2.0" for the 3.6 $\mu$m, 4.5 $\mu$m, 5.8 $\mu$m, and 8.0 $\mu$m bands respectively. The MIPS 24 $\mu$m beam has a FWHM as large as 6". Since confusion and blending effects are unavoidable in deep observations at this resolution, we decide not to degrade the space-based optical and NIR images to the MIR resolution.

Fig. 1.— Distributions of seeing FWHM for the ISAAC $J$, $H$, and $K_s$ observations. Moffat profiles were fitted to the PSFs that were built from bright, isolated, unsaturated stars for each field and band separately.
Table 2. H-band zero points in the AB system derived from the NIR stellar locus

| Field | H-band zero point |
|-------|-------------------|
| 03    | 25.99             |
| 04    | 26.02             |
| 05    | 26.07             |
| 08    | 25.89             |
| 09    | 25.92             |
| 10    | 25.94             |
| 11    | 25.93             |
| 13    | 26.02             |
| 14    | 25.82             |
| 15    | 26.07             |
| 16    | 25.97             |
| 19    | 25.86             |
| 20    | 25.89             |
| 21    | 25.97             |
| 22    | 26.03             |
| 23    | 26.07             |
| 24    | 25.95             |
| 25n   | 25.94             |
| 26n   | 26.09             |

3.3. Zero points

The zero-point calibrations for all bands but the H-band were taken from the respective GOODS data release. In the case of the NIR ISAAC observations, the publicly released zero points were based on SOFI images of the EIS-DEEP and DPS infrared surveys conducted over the same region (Vandame et al. 2001), which themselves were photometrically calibrated using standard stars from Persson et al. (1998). That procedure yielded zero points with rms scatters ranging between 0.01 and 0.06 mag in the J-band, 0.01 and 0.08 mag in the Ks-band and up to 0.17 mag in the H-band.

To improve on the H-band calibration, we make use of stellar photometry in the FIRES HDFS (L03) and MS1054–03 (FS06) fields, for which H-band zero points were determined to a ~0.03 mag accuracy. For each of the 19 ISAAC fields with H-band coverage, we measured the mean offset of the stars used for PSF matching along the J − H axis of a J − Ks versus J − H color-color diagram with respect to the stellar locus in the FIRES fields. Assuming the J- and Ks-bands are well calibrated, this immediately provides us with the H-band zero point corrections to be applied. We list the derived H-band zero points in Table 2. Zero-point corrections ranged from -0.18 mag to 0.09 mag, with a median correction over all fields of -0.03 mag. After applying the zero-point correction, the median absolute deviation in J − H color of individual stars around the stellar locus is 0.03 mag, similar as measured for the FIRES HDFS and MS1054–03 fields.

3.4. Mosaicing and astrometry

Here, we describe the combination of the smoothed ISAAC NIR fields and the astrometric precision of the final mosaics. The 5 × 5 blocked and smoothed ACS i775-band mosaic was adopted as astrometric reference image. The astrometric solution for the ACS data itself was based on a cross-identification of sources with deep ground-based WFI data that on its turn was astrometrically matched to stellar positions in the Guide Star Catalog 2 (GSC2, STScI 2001). The final solution had a 2σ-clipped rms deviation of ≤ 0′′01 in ACS-to-ACS and 0′′12 in ACS-to-ground difference.

The smoothed ISAAC fields were registered onto the smoothed ACS i775-band mosaic by applying simple x- and y- shifts without further distortion corrections. In each ISAAC field, we measured the shift with respect to the ACS i775-band mosaic for stars and compact sources using the imexam task in IRAF. A 2σ-clipped sample of reference sources typically consisted of 15-20 objects per ISAAC field. The 2σ-clipping was applied to exclude sources with strong morphological k-corrections. The difference between the shifts implied by individual reference sources and the final astrometric solution had a standard deviation of less than 0′′09 in all NIR bands. A map of residual shifts for the Ks-band mosaic with respect to the convolved ACS i775-band mosaic is presented in Fig. 2.

First we applied the fractional pixel shift for each ISAAC field in each band using the IRAF imshift task with a cubic spline interpolation. Next, we summed the integer pixel shifted fields applying an identical weighting scheme as described by FS06 to optimize the S/N for point sources, namely:

\[ w_{\text{pix}} = \frac{w_{\text{norm}}}{(\text{rms}_{1.5\text{FWHM}})^2} \]  

where the weight factor for a given pixel \( w_{\text{pix}} \) equals its value in the normalized weight map \( w_{\text{norm}} \), scaled with the square of the rms noise measured within apertures of 1.5FWHM diameter that are placed randomly in empty regions of the ISAAC field (see §3.5). Here, \( w_{\text{norm}} \) is simply the weight map as released by ESO/GOODS normalized to a maximum of unity. It thus contains information on the relative integration time per pixel and accounts for bad/hot pixels and pixels with other artifacts that were excluded. The weight maps for each field given by Eq. 1 were combined into a mosaic that accounts for the effective background noise over the entire area. In the catalog, we give the weight value for each object mea-
sured on this effective weight map, normalized to the median weight value in the considered band.

The standard deviation of positional offsets between reference sources on the registered WFI images and the $K_s$-band mosaic were less than 0.01.

We chose not to combine the 2 epochs of IRAC observations into one mosaic because the 180 degrees difference in position angle would lead to a different PSF shape in the overlap region than in either of both single epoch areas, demanding the use of a different convolving kernel over different parts of the field. Instead, we treat each of the IRAC epochs independently, providing an empirical quality check of the photometry in the overlap region. The registration of each of the IRAC images (epoch 1 and 2) onto the 2x2 blocked $K_s$-band image has a positional accuracy of better than 0.04, as measured from offsets between bright star positions on the IRAC and $K_s$-band images. The positional accuracy for the MIPS images is of the order of 0.3 rms. We note that minor positional offsets between the $K_s$ and IRAC/MIPS image are solved for by the source fitting algorithm applied to IRAC and MIPS photometry (see §4.2.0).

3.5. Signal to noise and limiting depths

We analyzed the noise properties of the optical-to-24 μm imaging following the same approach as for the FIRES HDFS (L03) and MS1054–03 (FS06) data. Briefly, the technique uses aperture photometry on empty parts of the image to quantify the rms of background pixels within the considered aperture size. For each convolved ISAAC field in each band, between 200 and 400 non-overlapping apertures were randomly placed at a minimum distance of 5" from the nearest segmentation pixels in a SExtractor segmentation map. For a given aperture size, the distribution of empty aperture fluxes is well-fitted by a Gaussian, as illustrated in Fig. 3(a). We applied a 5σ clipping in determining the background rms. Panel (b) of Fig. 3 shows that a simple linear scaling of the measured background rms $\sigma(N) = N\sigma_0$, where $N = \sqrt{A}$ is the linear size of the aperture with area A and $\sigma_0$ is the pixel-to-pixel rms, would lead to underestimated flux uncertainties. The reason is that correlations between neighboring pixels were introduced during the reduction and PSF matching. We model the background rms as a function of aperture size with a polynomial of the form

$$\sigma_i(N) = \frac{N\sigma_0(a_i + b_i N)}{\sqrt{w_i}}$$

where $i$ refers to the considered band and field, and the weight term $w_i$ is derived from the weight map of the respective field. Fig. 3(b) illustrates the variations in depth for the different ISAAC fields, originating from variable integration times and observing conditions, and reflected in the range of flux uncertainties for objects with similar color aperture in the final catalog. For example, the upper two curves in the ISAAC $K_s$ panel correspond to fields f03 and f04 that had the lowest integration time.

For the ACS mosaics, we used the same empty apertures as for the NIR, provided they were within the ACS FOV. Every object below the $K_s$-band detection threshold, even though detectable in the ACS imaging, contributes to the background noise and photometric uncertainties of $K_s$-band detected sources. If we were to restrict our empty aperture analysis to apertures that contain neither $K_s$-band nor ACS segmentation pixels, the background rms estimates for the ACS mosaics would decrease by 3 to 9%. In Fig. 3(b), we scaled the back-

![Fig. 3.— The background rms derived from the distribution of fluxes within empty apertures. (a) Distribution of empty aperture fluxes within a 1", 2", and 3" aperture diameter on the $K_s$-band image of ISAAC field f15. The distribution is well described by a Gaussian with an increasing width for increasing aperture size. (b) Background rms as derived from flux measurements within empty apertures versus aperture size for the ACS bands and the $J$, $H$, and $K_s$ ISAAC fields. Solid lines represent the functional form from Eq. 2 fit to the observed rms noise values. Dashed lines indicate a linear extrapolation of the pixel-to-pixel rms. Correlations between pixels introduce a stronger than linear scaling with aperture size.](image-url)
ground rms measured on the ACS and ISAAC images to the flux corresponding to $AB = 26$.

Uncertainties on the fluxes were assigned based on these empirical noise measurements, for an aperture of the same area as for the photometric aperture of each object.

Limiting depths of the WFI, IRAC, and MIPS images were measured with the same empty aperture method. The total limiting AB magnitudes ($3\sigma$ for point sources, i.e., corrected for the flux missed outside the aperture used for photometry) are listed in Table 1.

### 4. SOURCE DETECTION AND PHOTOMETRY

#### 4.1. $K_s$-band Detection

We aimed to construct a catalog that is especially suited to extract stellar mass-limited samples from (e.g., van Dokkum et al. 2006). Although the rest-frame NIR, probed by IRAC, is a better tracer for stellar mass than the rest-frame optical, the downside is its coarser resolution, leading to severe confusion. Therefore, we decided to detect sources in the observed $K_s$-band.

We used the SExtractor v2.2.2 source extraction software by Bertin & Arnouts (1996) to detect sources with at least 1 pixel above a surface brightness threshold of $\mu(K_s,AB) = 24.6$ mag arcsec$^{-2}$, corresponding to $\approx 5\sigma$ of the rms background for a typical $K_s$-band field. Setting the threshold to the same number of ADUs across the image instead of adopting a $S/N$ criterion was favored, since in the latter case the varying noise properties in the $K_s$-band mosaic would lead to different limiting magnitudes and limiting surface brightnesses from one field to the other. We smoothed the detection map with a gaussian filter of $FWHM = 0''65$, the size of the PSF in the detection image. This procedure optimizes the detection of point sources.

The resulting catalog contains 6308 sources, 5687 of which have a position on the $K_s$-band mosaic where the pixel weight is larger than 30% of the median weight. We recommend applying such a weight criterion in order to construct samples with robust photometry. Running SExtractor with identical parameters on the detection map multiplied by -1, we obtain a total of 43 spurious sources in the area with more than 30% of the median weight. Only one of these has $S/N_{K_s} > 5$.

SExtractor flagged 12% of the detected sources as blended and/or biased. These sources were treated separately in the photometry.

#### 4.2. Photometry

**Space-based optical and NIR photometry**

We performed the photometry on the convolved ACS $B_{435}, V_{606}, r_{775}, z_{850}$ and ISAAC $JHK_s$ mosaics using SExtractor in dual image mode, with the $K_s$-band mosaic as detection map. We derive the color and total aperture from the detection image. The same apertures were used in each band. We follow L03 and FS06 in defining the color aperture based on the $K_s$-band isophotal aperture, more precisely on the equivalent circularized isophotal diameter $d_{iso} = 2(A_{iso}/\pi)^{1/2}$, where $A_{iso}$ is the area of the isophotal aperture. For isolated sources, we apply

$$APER(COLOR) = \begin{cases} \text{APER(ISO)}, & d_{iso} < 2'' \text{0} \\ \text{APER(1''0),} & d_{iso} \leq 1'' \text{0} \\ \text{APER(2''0),} & d_{iso} \geq 2'' \text{0} \end{cases}$$

(3)

where $APER(ISO)$ refers to the isophotal aperture defined by the surface brightness detection threshold. Blended sources (indicated with SExtractor flag “blended” or “biased”) were treated separately,

$$APER(COLOR) = \begin{cases} \text{APER(d_{iso}/s),} & d_{iso}/s < 1'' \text{0} \\ \text{APER(1''0),} & d_{iso}/s \leq 1'' \text{0} \\ \text{APER(2''0),} & d_{iso}/s \geq 2'' \text{0} \end{cases}$$

(4)

where the reduction factor $s$ for the aperture sizes is introduced to minimize contamination by close neighbors. We adopt the optimal value of $s = 1.4$ that was determined from experimentation by L03 and FS06.

The motivation for the tailored isophotal apertures defined in Eq. 3 and Eq. 4 is that it maximizes the $S/N$ of the flux measurement. The minimum diameter of 1''0 corresponds to $1.5 \times FWHM$ of the PSF-matched mosaics. The maximum diameter of 2''0 was adopted to avoid flux from neighboring sources and avoid the large uncertainties corresponding to large isophotal apertures.

SExtractor’s “MAG_AUTO” was used to derive the total flux of the $K_s$-band detected objects, unless the source was blended, in which case the total aperture was set to the color aperture:

$$APER(TOTAL) = \begin{cases} \text{APER(AUTO), isolated sources} \\ \text{APER(COLOR), blended sources} \end{cases}$$

(5)

Finally, an aperture correction was applied to compute the total integrated flux. The correction factor equaled the ratio of the flux within an aperture of radius 3'' and radius $r_{tot} = (A_{tot}/\pi)^{1/2}$, based on the curve of growth of the PSF constructed from stellar profiles. Here, $A_{tot}$ represents the area of the total aperture. The reference aperture of 3'' radius is sufficiently large since less than 0.1% of the flux for point sources falls outside this radius.

Flux uncertainties in both color and total aperture were derived from Eq. 2. The quoted uncertainties thus take into account both the aperture size used for the flux measurement and the limiting depth in the respective region of the mosaic.

We performed a large number of simulations to determine the accuracy of our measurements of the total $K_s$-band magnitude. In each simulation, 200 artificial sources were added to the $K_s$-band mosaic. They had either exponential ($Sersic\ n=1$) or de Vaucouleurs ($Sersic\ n=4$) light profiles that were truncated at 5 effective radii, and random position angles and ellipticities. Source magnitudes and sizes were drawn from the true distribution in our catalog in order to span the entire range of real galaxy properties. Subsequently, we ran SExtractor with an identical configuration as for the real catalog, followed by the procedure to compute $K_{tot,AB}$ as described above. The recovered total magnitudes were within 0.1 (0.2) mag from the input value for 89 (96)% of the sources with exponential light profiles. Since our aperture corrections are based on the stellar growth
curve, our procedure could not account for all flux in the extended wings of low surface brightness sources with a high concentration (Sersic n=4). The recovered total magnitudes were within 0.1 (0.2) mag for 82 (91)% of the sources with de Vaucouleurs profiles. The sources where the $K_{\text{tot}}$AB underestimate exceeded 0.2 mag generally had $\mu_e > 22.5$ mag arcsec$^{-2}$. Taking into account the spread in Sersic indices for real sources in our catalog, we caution that underestimates of the total $K_s$-band magnitude by over 0.1, 0.2, and 0.3 mag could occur for roughly 13, 6, and 4% of the galaxies in our catalog, predominantly those with large size and low surface brightness.

**WFI, IRAC and MIPS 24 $\mu$m photometry**

In this section, we describe the photometry of $K_s$-band detected objects in the ground-based optical (WFI) and Spitzer IRAC and MIPS 24 $\mu$m imaging of the CDFS. For an in depth discussion of the source fitting algorithm used, and simulations of its performance, we refer the reader to Labbé et al. (in preparation). A short description with illustration was also presented by Wuyts et al. (2007).

Briefly, the information on position and extent of sources based on the higher resolution $K_s$-band segmentation map was used to model the lower resolution ground-based optical and 3.6 $\mu$m to 24 $\mu$m images. Each source was extracted separately from the $K_s$-band image and, under the assumption of negligible morphological k-corrections, convolved to the WFI, IRAC, respectively MIPS resolution. A fit to the WFI/IRAC/MIPS image was then made for all sources simultaneously, where the fluxes of the objects were left as free parameters. Next, we subtracted the modeled light of neighboring objects and measured the flux on the cleaned WFI/IRAC/MIPS maps within a fixed aperture: 2" for the WFI bands, 3" for the IRAC bands and 6" for the MIPS 24 $\mu$m band. In order to compute a consistent $K_s$-WFI/IRAC/MIPS color, we measured the source's flux $f_{\text{conv, } K_s}$ on a cleaned $K_s$-band image convolved to the WFI/IRAC/MIPS resolution within the same aperture. We then scaled the photometry to the same color apertures that were used for the space-based optical and NIR photometry, allowing a straightforward computation of colors over a $U_{38}$- to 8 $\mu$m wavelength baseline. For the IRAC photometry, this means the catalog flux was computed as follows:

$$f_{\text{IRAC, col}} = f_{\text{IRAC, 3''}} \times \frac{f_{\text{K_s, col}}}{f_{\text{conv, } K_s, 3''}}. \quad (6)$$

For the WFI photometry, an identical procedure was followed. An aperture correction based on the growth curve of the 24 $\mu$m PSF was applied to scale the 24 $\mu$m flux measurements to the integrated 24 $\mu$m flux under the assumption that the sources were point-like.

We note that several other authors developed similar algorithms to reduce the effects of confusion (Pérez-González et al. 2005, 2008; G06a). Pérez-González et al. (2005, 2008) compute SExtractor photometry for an IRAC-selected catalog that is later merged with shorter wavelength photometric catalogs. For the IRAC sources with multiple UV/optical/NIR counterparts within 2.5', the photometry was recomputed using a deconvolution method that is similar to that by Labbé et al. (in preparation), except for two aspects. The algorithm by Labbé et al. (in preparation) takes into account the spatial extent of the sources on the reference ($K_s$-band) image. Moreover, Labbé et al. (in preparation) does not adopt the best-fit flux from the source fitting as final photometry, but rather measures the flux within an aperture on the cleaned image (followed by an aperture correction). This allows more robust photometry in cases where the object profile varies from the reference to the low resolution image. A comparison with the multi-wavelength photometry by G06a is presented in §7.2.

Uncertainties in the measured fluxes in the WFI/IRAC/MIPS bands have a contribution from the background rms and from the residual contamination of the subtracted neighbors (Labbé et al., in preparation). The former was calculated using the empty aperture method described in §3.5. The latter was derived by scaling the normalized convolved $K_s$-band image of each neighboring source with the formal 1σ error in its fitted WFI/IRAC/MIPS flux as computed from the covariance matrix produced by the least-squares minimization. Subsequently, we performed aperture photometry on this image of residual neighbor contamination. This gives the confusion error corresponding to the source flux measured within an aperture of the same size. The two contributions were added in quadrature to obtain the total error budget. In the 3.6 $\mu$m band, where confusion is most severe, the confusion term is typically 5 times smaller than the background noise term. For 6% of the sources in our catalog, the confusion term dominates the total error budget.

Here, we follow an empirical approach to validate the size of the uncertainties in the IRAC photometry. We exploit the overlap region between the 2 independent observation epochs of the CDFS with the IRAC instrument. The position angle was rotated over 180 degrees, causing the PSF to have a different orientation with respect to the positions of neighboring sources. In Fig. 4, we show the difference between the IRAC magnitude measured during epoch 1 and epoch 2. The rms ranges from 5% in the 4.5 $\mu$m band to 10% in the 8.0 $\mu$m band for sources with an AB magnitude brighter than 22. The largest systematic offset was measured for the 3.6 $\mu$m band, where a zero-point drift of 0.03 mag was measured between the 2 epochs. In the inset panels the distribution of $(f_{\text{epoch1}} - f_{\text{epoch2}})/\sqrt{\text{err}^2_{\text{epoch1}} + \text{err}^2_{\text{epoch2}}}$ is plotted. The distribution is well described by a gaussian. For well estimated errors the expected standard deviation of the distribution is 1. We adopted a minimum relative uncertainty in the flux of 3% to account for zero-point variations over the field. This is particularly relevant for the 3.6 $\mu$m and 4.5 $\mu$m band, where the sources are detected with a high signal-to-noise. The standard deviation of $(f_{\text{epoch1}} - f_{\text{epoch2}})/\sqrt{\text{err}^2_{\text{epoch1}} + \text{err}^2_{\text{epoch2}}}$ in these bands is smaller than 1. Adopting a more conservative minimum relative uncertainty would only decrease this value, suggesting that zero-point variations within the field are limited to the few percent level. In the less sensitive 5.8 $\mu$m and 8.0 $\mu$m bands, where the minimum relative uncertainty is not reached, we find a distribution of $(f_{\text{epoch1}} - f_{\text{epoch2}})/\sqrt{\text{err}^2_{\text{epoch1}} + \text{err}^2_{\text{epoch2}}}$ with a standard deviation of nearly unity, confirming empirically the
validity of our estimated uncertainties.

5. REDSHIFTS

5.1. Spectroscopic redshifts

The CDFS-GOODS area has been targeted intensively by various spectroscopic surveys, listed in Table 3. The combined sample of spectroscopic redshifts forms a heterogeneous family of objects, with selection criteria varying from pure $I$-band (VVDS, Le Fèvre et al. 2004), $K_s$-band (Mignoli et al. 2005) or X-ray (Szokoly et al. 2004) flux limits to various color criteria (e.g., Doherty et al. 2005; Wuyts et al. in preparation). It is therefore impossible to build a complete $K_s$-band selected spectroscopic sample from the data at hand. Rather, we aim to provide a list of trustworthy spectroscopic redshifts that are reliably cross-identified with a $K_s$-band detection in our catalog. To do so, we apply a conservative quality cut based on the quality flags that come with each of the spectroscopic catalogs, and assign the redshift to the nearest $K_s$-band selected object within a radius of 1". The quality flags and number of sources included in our reliable list of cross-correlated spectroscopic redshifts are summarized in Table 3. We mark these sources with a “zsp_qual” flag of 1 in our catalog. For completeness, other spectroscopic redshifts for $K_s$-band detected objects are also listed in our catalog, marked with a “zsp_qual” flag lower than 1 (zsp_qual=0.5 for FORS2 quality flag B and VIMOS quality flag B, and zsp_qual=0.1 for all others), together with the original quality flag from the respective survey. We proceed to
Table 3. Spectroscopic redshifts for $K_s$-band detected objects

| Survey          | High quality flags | Number$^a$ |
|-----------------|--------------------|------------|
| FORS2 (v3.0, Vanzella et al. 2008) | A | 357 |
| K20 (Mignoli et al. 2005) | 1 | 265 |
| VVDS (v1.0, Le Fèvre et al. 2004) | 4, 3 | 251 |
| CXO (Sokoly et al. 2004) | 3, 2, 1 | 89 |
| Norman et al. 2002 | all | 1 |
| Croon et al. 2001 | all | 21 |
| van der Wel et al. 2004 | all | 24 |
| Cristiani et al. 2000 | all | 3 |
| Strolger et al. 2004 | all | 5 |
| Daddi et al. 2004 | all | 7 |
| IMAGES (Ravikumar et al. 2006) | 1 | 100 |
| LCIRS (Doherty et al. 2005) | 3 | 3 |
| Wuyts et al. (in prep.) | all | 7 |
| Kriek et al. (2007) | all | 2 |
| Roche et al. (2006) | all | 4 |
| Huang et al. (in prep.) | all | 9 |
| VIMOS (v1.0, Popesso et al. 2008) | A | 329 |

$^a$The numbers are non-redundant. For objects targeted during multiple surveys, the redshift with the highest quality flag was adopted.

use only the 1477 spectroscopic redshifts with $z_{sp,qual} = 1$.

5.2. Photometric redshifts

Together with the observed photometry, we release a list of photometric redshifts computed with the new photometric redshift code EAZY. A full description of the algorithm and template sets will be presented by Brammer et al. (in preparation). Briefly, the program fits a non-negative superposition of SED templates to the $U_3$-to-$8 \mu$m photometry, using a template error function that effectively downweights the rest-frame UV and rest-frame NIR of the templates in the fit. Next, a redshift probability distribution $p(z|C,m_0)$ is constructed for each galaxy with observed colors $C$, using the $K_s$-band magnitude $m_0$ as a prior. Finally, the value $z_{mp}$ of the redshift marginalized over the total probability distribution,

$$z_{mp} = \int z \frac{p(z|C,m_0)}{\int p(z|C,m_0)} dz,$$

was adopted as best estimate of the galaxy’s redshift. 1σ confidence limits were computed by integrating the redshift probability distribution from the edges till the integrated probability equals 0.317/2.

The template set constructed by Brammer et al. (in preparation) is based on PÉGASE models (Fioc & Rocca-Volmerange 1997). From a library of ~3000 templates described by G06a, Brammer et al. (in preparation) followed the “non-negative matrix factorization” algorithm of Blanton & Roweis (2007) in order to derive a set of 5 principal component templates that span the colors of galaxies in the semi-analytic model by De Lucia & Blaizot (2007). One dusty template with an age of 50 Myr and $A_V = 2.75$ was added to account for the existence of duster (and thus redder) galaxies than present in the semi-analytic model mock catalog. It is this set of 6 spectral templates that we fed to EAZY.

We quantify the accuracy of the photometric redshifts $z_{phot}$ by a comparison to the spectroscopic redshifts with $z_{sp,qual} = 1$. Fig. 5(a) shows the correspondence between $z_{phot}$ and $z_{spec}$ for all 1067 sources with $K_{s,AB} < 24.3$ that are covered by all bands and for which a reliable spectroscopic redshift is available. The error bars indicate the 1σ confidence intervals as derived from the redshift probability distribution. We find that the spectroscopic redshift lies within the formal 1σ confidence interval for 66% of the sources, confirming that the uncertainties on $z_{phot}$ have reliably been established.

Fig. 5(b) presents the distribution of $\Delta z/(1+z)$, with $\Delta z = z_{phot} - z_{spec}$, which is commonly used to determine the accuracy of photometric redshifts. We find a median $\Delta z/(1+z)$ of -0.001 and a normalized median absolute deviation (equal to the rms for a Gaussian distribution) of $\sigma_{NMAD} = 0.032$. 3% of the objects with spectroscopic redshift have $|\Delta z/(1+z)| > 5\sigma_{NMAD}$.

We investigated the quality of $z_{phot}$ estimates as a func-
tion of redshift and total $K_s$-band magnitude. Variations in the median $\Delta z/(1+z)$ as function of redshift are small, reaching a maximum of 0.05 in the $2.5 < z < 3$ interval. No obvious dependence on $K_{s,AB}^\text{tot}$ is observed. The scatter in $\Delta z/(1+z)$ is roughly a factor 2.4 larger for the $z > 1.5$ regime ($\sigma_{\text{NMAD}} = 0.071$) than for the $z < 1.5$ ($\sigma_{\text{NMAD}} = 0.030$) regime.

Considering the 98 spectroscopically confirmed sources with a cross-identification within 2′0 in the 1Ms X-ray catalog by Giacconi et al. (2002), we find a scatter of $\sigma_{\text{NMAD}} = 0.043$. It is reassuring that despite the lack of AGN spectrum in our template set, the netto performance of our photometric redshift code for AGN candidates remains good. We do note however that, independent of redshift, the fraction of catastrophic outliers ($|\Delta z/(1+z)| > 5\sigma_{\text{NMAD}}$) is 3 times larger for the AGN candidates than for the total sample of spectroscopically confirmed sources.

6. CATALOG PARAMETERS

Here we describe the entries of our $K_s$-band selected FIREWORKS catalog of the GOODS-CDFS. The format is similar to the FIREs catalogs of the HDFS (L03) and MS1054–03 (FS06), making a straightforward combination of all three fields possible for the user. The catalog can be obtained from the FIREWORKS homepage\(^1\).

- **ID**– Unique identification number
- **x, y**– Pixel position of the object, based on the $K_s$-band detection map. The pixel scale is 0′/15 pixel$^{-1}$.
- **RA, DEC**– Right ascension and declination coordinates for equinox J2000.0.
- **$[\text{band}]_{\text{colf}}$**– Flux in microjanskys measured within the color aperture (§ 4.2.0). The bandpasses are $U_{36},B_{435},V_{606},R_{775},I_{850},J,H,K_s$, $[3.6\mu m]$, $[4.5\mu m]$, $[5.8\mu m]$, and $[8.0\mu m]$.
- **$[\text{band}]_{\text{colf}}$**– Uncertainty in the $[\text{band}]_{\text{colf}}$ flux measurement, derived from the noise analysis (§ 3.5). The units are microjanskys.
- **$K_s^\text{totf}$**– Total $K_s$-band flux in microjanskys, measured within the total aperture and scaled by the aperture correction (§ 4.2.0). Approximate total fluxes in other bandpasses can be computed by $[\text{band}]_{\text{totf}} = [\text{band}]_{\text{colf}} \times (K_s^\text{totf}/K_s^\text{colf})$, provided there are no large morphological k-corrections.
- **$K_s^\text{totf}$**– Uncertainty associated with $K_s^\text{totf}$, also in microjanskys.
- **$[24\mu m]_{\text{totf}}$**– Total MIPS 24 $\mu m$-band flux in microjanskys, measured within a 6′ diameter circular aperture and then aperture corrected (§ 4.2.0).
- **$[\text{band}]w$**– Effective weight in the bandpass $[\text{band}]$, normalized to the median effective weight of all sources in that band. We recommend applying a conservative weight criterion $[\text{band}]w > 0.3$ to construct samples with robust photometry.
- **$ap_{\text{col}}$**– Aperture diameter in arcsec within which $[\text{band}]_{\text{colf}}$ was measured. In cases where the color aperture was the isophotal aperture defined by the surface brightness threshold of $\mu(K_{s,AB}) = 24.6$ mag arcsec$^{-2}$, $ap_{\text{col}}$ is the diameter in arcsec of a circular aperture with equal area.
- **$ap_{\text{tot}}$**– Aperture diameter in arcsec used for measuring the total $K_s$-band flux. When the isophotal or SEExtractor’s “MAG.AUTO” aperture was used, this entry contains the equivalent circularized diameter corresponding to that aperture.
- **f_deblend1**– Flag equal to 1 when the source was deblended somewhere in the process (SEExtractor’s “blend”).
- **f_deblend2**– Flag equal to 1 when the photometry is affected by a neighboring source (SEExtractor’s “bias”).
- **Kr50**– Half light radius in arcsec, measured on the $K_s$-band image (SEExtractor’s flux_radius scaled to arcsec).
- **Keps**– Ellipticity of the isophotal area, measured on the $K_s$-band image.
- **Kposang**– Position angle of the isophotal area, measured on the $K_s$-band image.
- **zph_best**– Best estimate of the photometric redshift ( § 5.2).
- **zph_low, zph_high**– Lower and upper edge of the 68% confidence interval around zph_best.
- **zsp**– Spectroscopic redshift (set to -99 when no spectroscopic information is available).
- **zsp_qual**– Quality flag from 0 to 1 assigned to the spectroscopic redshift. Only zsp_qual=1 entries are considered reliable.
- **zsp_source**– Spectroscopic survey from which zsp was taken (Tab. 3).
- **zsp_qual_orig**– Original quality flag for zsp from the respective spectroscopic survey.

7. COMPARISON TO THE GOODS-MUSIC CATALOG

7.1. Differences in data and strategy

Recently, G06a presented a multicolor catalog for the GOODS-CDFS field, referred to as the GOODS-MUSIC catalog. The clustering evolution of distant red galaxies was quantified based on this sample (Grazian et al. 2006b), as was the contribution of various color-selected samples of distant galaxies to the stellar mass density (Grazian et al. 2007). Despite the overlap in public data

\(^1\)http://www.strw.leidenuniv.nl/fireworks
used to compile the GOODS-MUSIC and our catalog, there are a number of marked differences.

First, our catalog is purely $K_s$-band selected. Since the $K_s$-band magnitude is a better proxy for stellar mass than the optical magnitude, this makes it ideally suited to extract mass-limited samples from. The GOODS-MUSIC sample on the other hand is to first order $z_{850}$-band selected (at the ACS resolution), with an addition of the remaining $K_s$-band sources that are detected in a map with masked $z_{850}$-band detections. Although valuable in its own respect, this makes it less trivial to understand the completeness of the sample.

Second, we based our catalog on the ESO/GOODS data release v1.5, consisting of 3 extra ISAAC pointings in $J$ and $K_s$, and 7 more in $H$ with respect to the v1.0 release used by G06a.

Third, apart from the $U_38$ photometry, we also added photometry based on images in the other WFI passbands: $BVRI$. Despite the shallower depth than the ACS imaging (see Table 1), this addition is useful for, e.g., estimating photometric redshifts, since the WFI passbands are nicely centered in between the ACS passbands. Consequently, the spectral energy distributions of sources in the catalog are better sampled.

Finally, we include MIPS 24 $\mu$m measurements, enabling us to constrain the total IR luminosity of the $K_s$-band selected galaxies. Before doing so, we compare the photometry in common between both catalogs, and the photometric redshifts derived from it.

7.2. Comparing photometry

We cross-correlated the two catalogs using a search radius of 1$''$2 and in Fig. 6 present a comparison of the $U_{38}$-to-8.0 $\mu$m photometry for the bands in common between them. Differences between the total magnitudes are plotted for objects with $S/N > 10$ in the $K_s$-band and the band under consideration. Objects that are marked by SExtractor as blended in the $K_s$-band, are indicated with empty symbols.

Our $U_{38}$ magnitudes for non-blended sources are fainter than the GOODS-MUSIC magnitudes by 0.2 magnitudes in the median, with a scatter of 0.4 magnitudes. This offset can be attributed to our use of the re-reduced WFI data for which the GaBoDS consortium also supplied an improved zeropoint determination.

The overall correspondence in the $B$-to-$K_s$ bands is good, and offsets can be well understood from the differences in the applied photometric method. We measure a typical median offset for non-blended sources in the optical and NIR bands of $mag_{\text{gal,FIREWORKS}} - mag_{\text{gal,MUSIC}} = -0.06$, and a scatter of $\sigma_{\text{NMAD}} < 0.2$. G06a based their total magnitudes on SExtractor’s “MAG_AUTO” parameter for the $z_{850}$-band detections and on the “MAG_BEST” for the remaining $K_s$-band detections that were not detected in the $z_{850}$-band. G06a did not apply an aperture correction based on the stellar growth curve to correct for the flux lost because it fell outside the “MAG_AUTO” or “MAG_BEST” aperture. The lack of aperture correction explains at least part of the systematic offset. Sources marked as blended in our $K_s$-band detection map typically are brighter by 0.2 - 0.4 mag in the MUSIC catalog. This can be explained by the contamination from neighboring sources within the “MAG_AUTO” aperture, which we avoid by using the isophotal aperture in combination with an aperture correction for blended sources. However, our measure of the total magnitude in the presence of crowding is also not perfect in that flux from the source that is projected on top of a blended source may be lost by our technique.

For the IRAC photometry, the discrepancies are larger, ranging from 0.16 mag in the 4.5 $\mu$m band to 0.42 mag at 8.0 $\mu$m. The observed offsets in IRAC photometry can largely be attributed to the use of an early version of the IRAC PSF by G06a and a bug in the normalization of the smoothing kernel for the IRAC data by G06a (Fontana & Grazian, private communication). After removing these two effects, our measurements of the total IRAC magnitudes are still brighter by 0.06 to 0.1 mag. This offset is similar to that for the optical and NIR bands, and can be attributed to light missed by the “MAG_BEST” magnitude, as G06a already caution. We stress that the offset in total IRAC magnitudes not only affects its derived properties such as stellar mass, but also the optical-to-MIR and NIR-to-MIR colors. For example, our $z_{850} - [3.6\mu m]$, $z_{850} - [4.5\mu m]$, $z_{850} - [5.8\mu m]$, and $z_{850} - [8.0\mu m]$ colors are redder than the GOODS-MUSIC colors by 0.23, 0.11, 0.17, and 0.37 mag in the median respectively. Similarly, our $K_s - [3.6\mu m]$, $K_s - [4.5\mu m]$, $K_s - [5.8\mu m]$, and $K_s - [8.0\mu m]$ colors are redder in the median by 0.29, 0.16, 0.22, and 0.42 respectively. The scatter in the color differences with respect to GOODS-MUSIC typically amounts to 1.5 times the size of the median offset.

7.3. Comparing photometric redshifts

Finally, we compare the photometric redshifts presented in §5.2 with those derived by G06a. The numbers quoted in §5.2 and by G06a cannot directly be compared since new spectroscopic redshifts were added, and objects that showed evidence for the presence of an AGN in their optical spectrum were rejected from the GOODS-MUSIC photometric redshift analysis. Nevertheless, when comparing the performance of the $z_{\text{phot}}$ estimates for a set of 659 non-AGN with reliable $z_{\text{spec}}$ and coverage in all bands in both catalogs, we find a scatter in $\Delta z/(1 + z)$ for GOODS-MUSIC ($\sigma_{\text{NMAD}} = 0.039$) that is similar to that for our best estimates ($\sigma_{\text{NMAD}} = 0.033$). The median $\Delta z/(1 + z)$ is -0.009 and -0.005 for the GOODS-MUSIC and FIREWORKS $z_{\text{phot}}$ estimates respectively.

Comparing the $z_{\text{phot}}$ estimates for all objects that are well exposed in all bands in both catalogs, irrespective of a spectroscopic confirmation, we find a median $z_{\text{phot,MUSIC}} - z_{\text{phot,FIREWORKS}}^{\text{1+}}$ of 0 and a scatter $\sigma_{\text{NMAD}} = 0.052$. The largest systematic offsets occur in the $1.5 < z < 2$ and $2.5 < z < 3$ intervals where median($z_{\text{phot,MUSIC}} - z_{\text{phot,FIREWORKS}}^{\text{1+}}$) $\sim$ 0.04 and -0.04 respectively. We find no systematic dependence on $K_s$-AB.

We conclude that the photometric differences between both catalogs can be understood from the applied method. Our $z_{\text{phot}}$ estimates are in excellent agreement with the available spectroscopic samples and generally show good agreement with the $z_{\text{phot}}$ estimates by G06a. We now proceed to exploit our catalog to analyze the colors and total IR energy output of distant galaxies.

8. TOTAL IR PROPERTIES OF DISTANT $K_S$-SELECTED GALAXIES
Fig. 6.— A direct comparison of total magnitudes for sources with \( S/N > 10 \) in the \( U_{38} \)-to-8.0 \( \mu m \) bandpasses in common between GOODS-MUSIC and our FIREWORKS catalog. Sources that are blended in the \( K_s \)-band image are plotted as empty symbols. On the right side of each panel, a histogram shows the distribution of offsets. Our \( U_{38} \) photometry, based on the re-reduced WFI image by the GaBoDS consortium, is systematically fainter by 0.2 mag. We find an overall good correspondence in the ACS optical and ISAAC NIR bands, with offsets of roughly 6% due to aperture corrections. In the IRAC bands, photometric offsets amount up to 0.4 mag.

With the catalog at hand, we aim to answer the following simple questions: Which \( K_s \)-selected \( (S/N_{K_s} > 5, K_{tot}^{AB} \lesssim 24.3) \) galaxies at \( 1.5 < z < 2.5 \) have the brightest total IR luminosities \( (L_{IR} \equiv L(8 - 1000 \mu m)) \), and which contribute most to the integrated total IR luminosity? Specifically we will address whether the total IR luminosity is dominated by red or blue galaxies, with the color defined in the rest-frame UV, optical or NIR wavelength regime. We restrict our analysis to the \( 1.5 < z < 2.5 \) interval, since at those redshifts the observed 24 \( \mu m \) probes the rest-frame mid-IR \( (7 \mu m \lesssim \lambda_{rest} \lesssim 10 \mu m) \), which broadly correlates with the total IR luminosity (e.g., Spinoglio et al. 1995; Chary & Elbaz 2001; Dale & Helou 2002).

8.1. Observed 24 \( \mu m \) flux as function of observed colors

We approach the questions raised above by first studying the correlation between purely observational properties: the 24 \( \mu m \) flux as proxy for IR luminosity and the observed \( B_{435} - V_{606}, J - K_s \), and \( K_s - [4.5\mu m] \) colors as proxy for the rest-frame UV, optical and optical-to-NIR color respectively. Unless the redshift dependence of the conversion from 24 \( \mu m \) to total IR luminosity and of the conversion from observed to rest-frame colors are conspiring, any trend in the directly observable properties should be a signpost for correlations in the rest-frame
properties, whose derivation involves significant systematic uncertainties.

The total number of $K_s$-selected galaxies at $1.5 < z < 2.5$ with $K^\text{tot}_{s,AB} < 24.3$ is 961. 45% of these are individually detected at the 3$\sigma$ level ([24$\mu$m]$_{\text{tot}} > 11$ $\mu$Jy). Since we aim to investigate what color galaxies dominate the IR emission, we divide our galaxies in bins of similar color. Each bin contains an equal number of sources (160). Consequently, the bin widths are not equal. To start, we leave the origin of the 24 $\mu$m emission (dust heated by AGN or star formation) as an open question. We note however that when excluding X-ray detected sources each bin would contain 154 objects, and applying such a selection would not affect the results of our analysis. We perform the stacking per color bin in two ways: by averaging the 24 $\mu$m flux measurements of all sources in the bin (some of which will be negative due to noise), and by taking the median of the 24 $\mu$m flux measurements of all sources in the bin. The mean has a contribution from all the galaxies in the color bin, and hence directly measures the contribution to the integrated 24 $\mu$m emission. The median has the advantage that it is more robust against a small number of bright sources in the color bin, and is therefore lower.

In Fig. 7, the stacked 24 $\mu$m flux densities are plotted versus the observed $B_{435} - V_{606}$, $J - K_s$, and $K_s - [4.5\mu m]$ color. The error bars on the mean flux measurement indicate the errors in the mean ($\sigma([24]\mu m)_{\text{tot}}/\sqrt{N}$), whereas the error bars on the median flux measurement are computed as $\Delta_{\text{NMA}} ([24]\mu m)_{\text{tot}}/\sqrt{N}$. Furthermore, the light grey and dark grey polygon show the range containing respectively the central 68% and 50% of the binned galaxies. Each color bin contains galaxies with a large spread in 24 $\mu$m fluxes. In most bins, at least 20% of the galaxies have an individual signal-to-noise ratio $S/N < 1$ at 24 $\mu$m. Fig. 7(a) shows that the galaxies in the bluest $B_{435} - V_{606}$ bins are the faintest 24 $\mu$m sources. However, the stacked [24$\mu$m]$_{\text{tot}}$ flux is not uniformly increasing over the whole observed optical color range. Considering colors measured at longer wavelengths, we find a highly significant increase in the stacked [24$\mu$m]$_{\text{tot}}$ flux over the entire $J - K_s$ (Fig. 7(b)) and $K_s - [4.5\mu m]_{\text{tot}}$ (Fig. 7(c)) color range. The trend is strongest in the observed $K_s - [4.5\mu m]_{\text{tot}}$ color, where we find an increase in [24$\mu$m]$_{\text{tot}}$ of a factor 26 in the mean and 2 orders of magnitude in the median over a color range of $\sim 1.3$ mag. Since the bins contain an equal number of objects, it is trivial to see that not only the reddest galaxies in $J - K_s$ and $K_s - [4.5\mu m]$ are brightest at 24 $\mu$m, they also contribute the most to the total 24 $\mu$m emission integrated over all $K_s$-selected galaxies at $1.5 < z < 2.5$.

8.2. Total IR luminosity as function of rest-frame colors

Although the trend of more 24 $\mu$m emission for galaxies with a redder observed color is highly significant for $J - K_s$ and $K_s - [4.5\mu m]$, it could still be contaminated or, alternatively, driven by redshift dependencies within the $1.5 < z < 2.5$ redshift interval under consideration. Now, we will attempt to remove possible redshift dependencies by converting both axes to a rest-frame equivalent. Moreover, instead of converting the measured flux density at 24 $\mu$m to a rest-frame flux density at 24 $\mu$m/(1 + z), we use it as a probe to determine the

![Fig. 7](image-url). Stacked 24 $\mu$m flux densities as function of observed $B_{435} - V_{606}$, $J - K_s$, and $K_s - [4.5\mu m]$ color for galaxies at $1.5 < z < 2.5$ with $S/N > 5$ in the $K_s$-band (corresponding to $K^\text{tot}_{s,AB} \lesssim 24.3$). Filled circles represent the median for each equal-number bin. Empty boxes represent the mean flux. Light-grey and dark-grey polygons indicate respectively the central 68% and 50% of the distribution within each bin. We find a trend of increasing [24$\mu$m]$_{\text{tot}}$ with redder observed-frame color that gets progressively stronger as we consider colors measured at longer wavelengths.
total IR luminosity $L_{\text{IR}} = L(8 - 1000 \, \mu m)$. Since this conversion assumes that the $24 \, \mu m$ emission originates from dust heated by star formation, we further reject all X-ray detections from our sample to rule out relatively unobscured AGN candidates. We caution that among the brightest $24 \, \mu m$ sources in our sample, there may still be cases where hot dust emission from an obscured AGN contributes significantly to the $24 \, \mu m$ emission and causes an overestimate of $L_{\text{IR}}$. Detailed studies of such mid-IR excess sources are presented by Daddi et al. (2007) and Papovich et al. (2007). Papovich et al. (2007) find that for sources with $[24 \mu m]_{\text{tot}} > 250 \, \mu Jy$ the $L_{\text{IR}}$ estimates derived from the $24 \, \mu m$ flux density alone are too large by factors 2-10. We stress however that we study a deep $K_s$ and not $24 \, \mu m$-selected sample. The fraction of sources with $[24 \mu m]_{\text{tot}} > 250 \, \mu Jy$ per color bin never exceeds 7%. Therefore, at least the median stacked properties are relatively robust against a possible contamination by obscured AGN.

In the following, we first describe the derivation of rest-frame UV to NIR colors. Next, we explain the method to estimate the total IR luminosity. Finally, we repeat the stacking analysis using the derived rest-frame properties.

**Stellar mass, UV slope, and rest-frame colors**

For each of the galaxies in our sample, we modeled the spectral energy distribution (SED) using the stellar population synthesis code by Bruzual & Charlot (2003). We used an identical approach as Wy advertise et al. (2007), assuming a Salpeter IMF and solar metallicity, and fitting three star formation histories: a single stellar population without dust, an exponentially declining model with e-folding time of 300 Myr and allowed dust attenuation in the range $A_V = 0 - 4$, and a constant star formation model with the same freedom in attenuation. We subsequently scaled the stellar masses derived from the best-fitting template to a Kroupa IMF by dividing the stellar masses for a Salpeter IMF by a factor 1.6.

We characterize the rest-frame UV part of each SED by fitting the functional form $F_{\lambda} \sim \lambda^\beta$ to the best-fitting template, using the rest-frame UV bins defined by Calzetti, Kinney, & Storchi-Bergmann (1994). The robustness of this technique is discussed by van Dokkum et al. (2006).

The rest-frame $(U - V)_{\text{rest}}$ and $(V - J)_{\text{rest}}$ colors were determined by interpolation between the directly observed bands using templates as a guide. For an in depth discussion of the algorithm, we refer the reader to Rudnick et al. (2001; 2003). We used an IDL implementation of the algorithm by Taylor et al. (in preparation) dubbed “InterRest”.

**Converting 24 $\mu m$ flux to total IR luminosity**

At redshifts $1.5 < z < 2.5$, the $24 \, \mu m$ fluxes trace the rest-frame $7.7 \, \mu m$ emission from polycyclic aromatic hydrocarbons (PAHs). To convert this MIR emission to a total IR luminosity $L_{\text{IR}} = L(8 - 1000 \, \mu m)$, we use the infrared spectral energy distributions of star-forming galaxies provided by Dale & Helou (2002). The template set allows us to quantify the IR/MIR flux ratio for different heating levels of the interstellar environment, parameterized by $dM(U) \sim U^{-\alpha}dU$ where $M(U)$ represents the dust mass heated by an intensity $U$ of the interstellar radiation field.

We computed the total infrared luminosity $L_{\text{IR},\alpha}$ for each object for all Dale & Helou (2002) templates within the reasonable range from $\alpha = 1$ for active galaxies to $\alpha = 2.5$ for quiescent galaxies. The mean of the resulting $\log (L_{\text{IR},\alpha=1.0625,...,2.5})$ was adopted as best estimate for the IR luminosity, and the $\pm 0.45$ dex variation from $L_{\text{IR},\alpha=2.5}$ to $L_{\text{IR},\alpha=1}$ was taken as a measure for the systematic uncertainty in the conversion.

Apart from the random photometric error and systematic template uncertainty, uncertainties in the photometric redshift contribute to the total error budget. For each galaxy, we calculated the spread in $L_{\text{IR}}$ caused by variations of $z_{\text{phot}}$ within the 68% confidence interval. Although the uncertainty in photometric redshift is partly random (propagating from photometric uncertainties in the SED), we treat it as purely systematic, originating from template mismatches. This means the error bars related to $z_{\text{phot}}$ on the stacked $L_{\text{IR}}$ measurements do not scale with $1/\sqrt{N}$. Instead, they range from the stacked $L_{\text{IR}}$ based on the lowest $L_{\text{IR},\text{individual}}$ estimates allowed for each object within its $z_{\text{phot}}$ uncertainty, to the stacked $L_{\text{IR}}$ based on the maximum $L_{\text{IR},\text{individual}}$ allowed for each object.

**$L_{\text{IR}}$ versus rest-frame color**

Having determined the rest-frame colors and total IR luminosities of $K_s$-selected galaxies without X-ray detection at $1.5 < z < 2.5$, we now proceed to investigate which $K_s$-selected galaxies contribute most to the IR emission. Again, we investigate the average properties of galaxies binned by color to enhance the robustness of our results. In Fig. 8, we plot the mean and median total IR luminosities of our in color bins divided sample versus the rest-frame UV slope $\beta$, the rest-frame optical color $(U - V)_{\text{rest}}$, and the rest-frame optical-to-NIR color $(V - J)_{\text{rest}}$. The black error bars indicate the error in the mean, respectively median. With dotted error bars, we show the systematic variations allowed within the photometric redshift uncertainties. Finally, the error bar in the bottom right corner represents the range from quiescent to active galaxy templates by Dale & Helou (2002). Clearly, systematic uncertainties are dominating the error budget in this analysis.

As in Fig. 7, we find a large range in IR properties within each bin, illustrated by the light grey and dark grey polygons that mark respectively the central 68% and 50% of the distribution of $L_{\text{IR}}$ of individual objects. Nevertheless, a general trend is visible of redder colors corresponding to larger IR luminosities. No matter which part of the spectral energy distribution is used to define red or blue galaxies, the redder half of the galaxies in our sample have stacked IR properties in the LIRG ($L_{\text{IR}} = 10^{11} - 10^{12} L_\odot$) regime. The trend seems to flatten at the reddest UV slopes, and the contribution to the total IR luminosity even drops for the reddest $(U - V)_{\text{rest}}$ bin. In $(V - J)_{\text{rest}}$ on the other hand, the increase in $L_{\text{IR}}$ with reddening color continues over the entire color range, reaching ULIRG luminosities ($L_{\text{IR}} > 10^{12} L_\odot$) for 23% of the galaxies in the reddest bin.

Considering the IR luminosities of individual objects over the entire color range, we find that ULIRGs make up 7% of our $K_s$-selected sample with $K_{s,\text{AB}} < 24.3$. The fraction of ULIRGs increases to 35% when only consider-
Fig. 8.— Stacked total IR luminosities as function of rest-frame UV slope, \((U-V)_{\text{rest}}\), and \((V-J)_{\text{rest}}\) for non-AGN at \(1.5 < z < 2.5\) with \(S/N > 5\) in the \(K_\alpha\)-band \((K_{s,\text{AB}} < 24.3)\). Filled circles represent the median for each equal-number bin. Empty boxes represent the mean flux. Light-grey and dark-grey polygons indicate respectively the central 68% and 90% of the distribution within each bin. The systematic uncertainty induced by template uncertainties in the conversion to \(L_{\text{IR}}\) is indicated in the bottom right corner. The dotted error bars indicate the variation in the mean and median \(L_{\text{IR}}\) by systematic variations in \(z_{\text{phot}}\). We find a trend of increasing \(L_{\text{IR}}\) with redder rest-frame color. Since the bins contain equal numbers of objects, this also means that red galaxies contribute most to the integrated IR emission of distant \(K_\alpha\)-selected galaxies.

The IR/MIR conversion factor varies by nearly an order of magnitude between the use of quiescent \((\alpha = 2.5)\) or active \((\alpha = 1)\) galaxy templates. For each of the galaxies, we used the mean of the logarithm of all conversion factors derived from the \(1 \leq \alpha \leq 2.5\) templates. Other authors (e.g. Papovich et al. 2006; Papovich et al. 2007) adopted a conversion to total IR luminosity in which the rest-frame IR luminosity density translates uniquely to a single SED template (i.e., a lower \(\alpha\) was used for brighter galaxies). Applying the conversion by Papovich et al. (2007) to each of the galaxies in our sample and repeating the stacking procedure, gives the following results. The mean \(L_{\text{IR}}\) for each color bin increases by typically \(\sim 0.1\) dex with respect to the value obtained with our universal (flux-independent) conversion. The median \(L_{\text{IR}}\) for each color bin instead decreases by typically \(\sim 0.15\) dex. All the described correlations between \(L_{\text{IR}}\) and rest-frame color remain intact. We thus confirm that our results are robust to alternative conversions from 24 \(\mu\)m flux to total IR luminosity that are commonly used in the literature.

We conclude that amongst distant \(K_\alpha\)-selected galaxies that show no sign of relatively unobscured AGN at X-ray wavelengths, the redder galaxies have on average larger total IR luminosities. Given that each bin in Fig. 8 contains an equal number of objects, it is also clear that red galaxies in our sample contribute more to the integrated total IR luminosity than blue galaxies. We argue that this trend cannot be explained by systematic errors, and tested that this conclusion is robust against the precise choice of redshift interval by varying the lower edge between redshift 1 and 2 and the upper edge between 2 and 3. Likewise, we verified that none of our conclusions critically depend on the number of color bins. Finally, we note that, although X-ray detections were excluded from our analysis to validate the use of IR templates for starforming galaxies, the results remain nearly unaffected when we treat them as normal galaxies.

Dividing the sample in two equal-number bins according to \(\beta\), \((U-V)_{\text{rest}}\), and \((V-J)_{\text{rest}}\), we find that the integrated total IR luminosity of the red half is larger than that of the blue half by a factor \(6.7 \pm 1.6\), \(3.6 \pm 0.8\), and \(5.6 \pm 1.2\) respectively. Imposing a brighter cut in the \(K_\alpha\)-band magnitude (Fig. 9) weakens the correlation of \(L_{\text{IR}}\) with UV slope and \((V-J)_{\text{rest}}\). Adopting a \(K_{s,\text{AB}} < 22.86\) cut, as is the case for the NIR-selected sample studied by Reddy et al. (2006), causes the stacked \(L_{\text{IR}}\) of the bluest \((U-V)_{\text{rest}}\) colors to increase while the stacked \(L_{\text{IR}}\) of the reddest \((U-V)_{\text{rest}}\) colors drops. The overall fraction of galaxies that is not detected at the 3\(\sigma\) level in the 24 \(\mu\)m band is lower by a factor 2 in the \(K_{s,\text{AB}} < 22.86\) sample than in our \(K_{s,\text{AB}} < 24.3\) sample. However, at the reddest optical colors \(((U-V)_{\text{rest}} > 1.3)\) the fraction of galaxies that is not detected at the 3\(\sigma\) level in the 24 \(\mu\)m band remains the same as we impose the brighter \(K_\alpha\)-band limit. We find that, for this \(K_\alpha\)-bright sample, the ratio of the integrated \(L_{\text{IR}}\) of the red and the blue half of the galaxies in \(\beta\), \((U-V)_{\text{rest}}\), and \((V-J)_{\text{rest}}\) amounts to a factor of \(2.1 \pm 0.5\), \(1.2 \pm 1.1\), and \(2.1 \pm 0.5\) respectively.

It is tempting to elaborate on the physical interpreta-
tion in terms of star formation rate (SFR), age, and dust content of the galaxies in our sample implied by the presented results. Colors in different wavelength regimes are to a greater or lesser extent determined by these physical parameters. The UV slope and \((V - J)_{\text{rest}}\) color are both sensitive tracers of dust attenuation (Meurer et al. 1999 and Wuyts et al. 2007 respectively). In comparison to the \((V - J)_{\text{rest}}\) color, the \((U - V)_{\text{rest}}\) color is more sensitive to stellar age and to lesser extent affected by dust (Wuyts et al. 2007). The fact that in the reddest \((U - V)_{\text{rest}}\) bin the total IR luminosity drops again might therefore indicate an increasing contribution from low \(L_{\text{IR}}\) galaxies with little dust-obscured star formation. In combination with the fact that rest-frame optically selected galaxies often have faint UV luminosities and thus little unobscured star formation (Förster Schreiber et al. 2004), this suggests that part of the galaxies making up the reddest \((U - V)_{\text{rest}}\) bin have a low overall SFR (unobscured + obscured). This is consistent with the spectral evidence for galaxies with quenched star formation at \(z \sim 2\) (Kriek et al. 2006). A similar conclusion was drawn by Reddy et al. (2006), who found for a sample of galaxies at similar redshifts selected by optical and NIR color criteria that the IR luminosity of 24 \(\mu\)m detected sources increased toward redder observed \(z - K\), but that at the reddest \(z - K\) colors a population without 24 \(\mu\)m detection exists that satisfies the Distant Red Galaxy (Franx et al. 2003) and/or BzK/PE (Daddi et al. 2004) color criteria. Based on X-ray stacking in the GOODS-North field, although also probing only to \(K_{\text{rest}} < 22.86\), Reddy et al. (2005) found a similar turnover in inferred SFR at \(z - K > 3\). Although the observed \(z - K\) color is redshift dependent and at \(z \sim 2\) spans a somewhat broader wavelength range than \((U - V)_{\text{rest}}\), both colors probe the age-sensitive Balmer/4000Å break and the observed turnovers therefore likely share the same origin.

An in depth analysis of the mix between dust-obscured starforming systems and evolved red galaxies would require a careful SED modeling, estimating the SFR based on different wavelength tracers from X-ray over UV to the infrared, and a treatment of each object on an individual basis to assess their relative contribution. Such a study is clearly beyond the scope of this paper, and will be presented by Labbé et al. (in preparation) based on the combined sample of galaxies in the CDFS (this paper), MS 1054–03 (FS06) and the HDFS (L03).

**Redshift dependence**

We measure a median rest-frame color evolution for galaxies in our \(K_{s,\text{rest}} < 24.3\) sample from \(z = 2.5\) to \(z = 1.5\) of 0.48, -0.05, and 0.48 for \(\beta\), \((U - V)_{\text{rest}}\), and \((V - J)_{\text{rest}}\) respectively. We note that going to lower redshifts, the evolution in \(\beta\) and \((V - J)_{\text{rest}}\) reverses. The observed evolution amounts to 26, 5, and 40\% of the scatter in the respective rest-frame color at any given redshift in the \(1.5 < z < 2.5\) range. Consequently, not every color bin in Fig. 8 and Fig. 9 is composed of galaxies with exactly the same redshift distribution. This is particularly the case for \(\beta\) and \((V - J)_{\text{rest}}\), where the measured color evolution with redshift is largest. A dependence on redshift can potentially affect the observed trend of increasing \(L_{\text{IR}}\) toward redder colors, if \(L_{\text{IR}}\) evolves within the \(1.5 < z < 2.5\) interval. Binning galaxies by redshift, we find

![Fig. 9](image_url)
a decrease in the stacked $L_{\text{IR}}$ from $z = 2.5$ to $z = 1.5$ by $\sim 0.4$ dex. We conclude that redshift dependencies within the $1.5 < z < 2.5$ interval are not driving, and if anything weaken, the observed increase of $L_{\text{IR}}$ toward redder colors.

**Mass dependence**

We now investigate the role of stellar mass in the observed trend of red galaxies dominating the total IR emission. van Dokkum et al. (2006) showed that the high-mass end of the redshift galaxy population is dominated by galaxies with red $(U-V)_{\text{rest}}$ and large $\beta$. Considering the optical-to-NIR colors of galaxies in our sample, a similar lack of massive galaxies with blue $(V-J)_{\text{rest}}$ is observed.

In order to investigate whether the $L_{\text{IR}}$ - color relation discussed in §8.2.0 merely reflects a correlation between stellar mass and $L_{\text{IR}}$, we now divide out the mass dependence. Fig. 10 shows the stacked $L_{\text{IR}}/M_*$ measurements as a function of color for the $K_{s,\text{AB}}^\text{tot} < 24.3$ sample and the $K_{s,\text{AB}}^\text{tot} < 22.86$ subsample. The y-axes span 4 orders of magnitude, as in Fig. 8 and Fig. 9, allowing an easy visual comparison of the strengths of the trends. A weaker trend, by up to an order of magnitude, is observed between $L_{\text{IR}}/M_*$ and rest-frame color than between $L_{\text{IR}}$ and rest-frame color (Fig. 8 and Fig. 9). For the $K_s$-bright subsample ($K_{s,\text{AB}} < 22.86$), the observed $L_{\text{IR}}$ versus $\beta$ and $L_{\text{IR}}$ versus $(V-J)_{\text{rest}}$ relation can even be entirely attributed to a dependence on color on stellar mass. Finally, the drop in stacked $L_{\text{IR}}/M_*$ at the reddest $(U-V)_{\text{rest}}$ colors is stronger than the drop in stacked $L_{\text{IR}}$. The population of optically red galaxies with only little IR emission, suggested by the analysis in §8.2.0, therefore concerns galaxies at the high-mass end of the mass function.

**9. SUMMARY**

We present a $K_s$-band selected catalog for the GOODS-CDFS, dubbed FIREWORKS, containing consistent photometry in the $U_{38}$, $B_{335}$, $B$, $V$, $V_{606}$, $R$, $i_{775}$, $I$, $z_{850}$, $J$, $H$, $K_s$, $[3.6\mu m]$, $[4.5\mu m]$, $[5.8\mu m]$, $[8.0\mu m]$, and $[24\mu m]$ bands. Together with the photometry, we release a list of photometric redshifts with a scatter in $\Delta z/(1+z)$ of 0.032, a cross-correlation with all available spectroscopic redshifts to date, and a cross-correlation with the 1Ms X-ray catalog by Giacconi et al. (2002). After a description of the catalog construction, we discuss the differences with the GOODS-MUSIC $z_{850}$ + $K_s$-selected catalog by G06a.

A previous version of the catalog, lacking the WFI $U_{38}BVRI$ photometry, has been used to estimate stellar mass densities (Rudnick et al. 2006), construct luminosity functions (Marchesini et al. 2006) and study the predominance of red galaxies at the high mass end (van Dokkum et al. 2006). In this paper, we exploit the full catalog to answer the following question: Which distant $K_s$-band selected galaxies are brightest and contribute most to the total IR luminosity?

First, we compared the stacked $24 \mu m$ fluxes of galaxies at $1.5 < z < 2.5$ with $K_{s,\text{AB}}^\text{tot} < 24.3$ split in observed color bins. Overall, a large spread in IR properties is found in each color bin. Nevertheless, stacking the fluxes within each bin reveals a clear trend with color. Both in the observed $B_{335} - V_{606}$, $J - K_s$, and $K_s - [4.5\mu m]$ colors, the lowest mean and median $[24\mu m]_\text{tot}$ fluxes are found for the bluest color bin. In $J - K_s$ and $K_s - [4.5\mu m]$, the emission at $24 \mu m$ continues to rise toward redder colors.

Second, we use our photometric redshifts to convert the observed spectral energy distributions to rest-frame colors and translate the observed $24 \mu m$ flux to the total IR luminosity $L_{\text{IR}} \equiv L(8 - 1000 \mu m)$. In this procedure, all relatively unobscured AGN candidates, selected by their X-ray detection, were rejected from the sample. Removing the redshift dependence and extrapolating from MIR to total IR comes at the cost of systematic uncertainties. We carefully measured the systematic contribution to the total error budget from uncertainties in $z_{\text{phot}}$ and from our lack of knowledge about which IR template SED matches best the spectral shape of the objects in our sample. Doing so, we find a continuous increase in $L_{\text{IR}}$ with $(V-J)_{\text{rest}}$. An increasing $L_{\text{IR}}$ is also measured with UV slope $\beta$, flattening at the largest $\beta$. The rising trend of the stacked $L_{\text{IR}}$ luminosity toward redder $(U-V)_{\text{rest}}$ seems to reverse in the reddest color bin. The large range of total IR properties in this bin suggests a mixture of galaxies with large amounts of dust emission (LIRGs up to ULIRGs) and objects devoid of it. We note that, if we were to apply a different translation from MIR to total IR luminosity than simply averaging over the conversion factors derived from all reasonable templates, the observed trends remain intact. This is e.g. the case when an SED template corresponding to a larger heating intensity of the interstellar radiation field is used for objects with a larger rest-frame IR luminosity density, as done by Papovich et al. (2006; 2007).

Since we divide our $K_s$-band selected sample in bins containing equal numbers of objects, it is immediately clear that not only do red galaxies have on average the largest total IR luminosities, it is also true that they form the dominant contribution to the overall total IR luminosity emitted by $K_s$-selected galaxies at $1.5 < z < 2.5$. We show that the dependence of both color and $L_{\text{IR}}$ on stellar mass is an important driver of, but cannot fully explain the observed trends of $L_{\text{IR}}$ with color.

We thank Adriano Fontana and Andrea Grazian for useful discussions about the photometric aspect of this work. SW acknowledges support from the W. M. Keck Foundation. Support from NSF CAREER grant AST 04-49678 is gratefully acknowledged. Observations have been carried out using the Very Large Telescope at the ESO Paranal Observatory under Program IDs LP168.A-0485, 170.A-0788, 074.A-0709, 275.A-5060, and 171.A-3045.

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Fig. 10.— Stacked total IR luminosity divided by stellar mass as function of rest-frame UV slope, \((U-V)_{\text{rest}}\), and \((V-J)_{\text{rest}}\) for non-AGN at 1.5 < \(z\) < 2.5 with \(K_{\text{sub}}^\text{tot, AB} < 24.3\) (left panels) and \(K_{\text{sub}}^\text{tot, AB} < 22.86\) (right panels). Symbols are identical to those in Fig. 8 and Fig. 9. The stacked \(L_{\text{IR}}/M_\star\) shows a weaker increase with rest-frame color than the stacked \(L_{\text{IR}}\) (Fig. 8 and Fig. 9), and is nearly independent of \(\beta\) and \((V-J)_{\text{rest}}\) for the \(K_{\text{sub}}^\text{tot, AB} < 22.86\) subsample. A drop in the stacked \(L_{\text{IR}}/M_\star\) at the reddest \((U-V)_{\text{rest}}\) is clearly observed.
