SPITZER ULTRA FAINT SURVEY PROGRAM (SURFS UP). I. AN OVERVIEW*

MARUŠA BRADAC1, RUSSELL RYAN2, STEFANO CASERTANO2, KUANG-HAN HUANG1, BRIAN C. LEMAUX3, TIM SCHRABBACK4, ANTHONY H. GONZALEZ5, STEVE ALLEN6, BENJAMIN CAIN1, MIKE GLADDERS7, NICHOLAS HALL1, HENDRIK HILDEBRANDT4, JOANNAH HINZ8, ANJA VON DER LINDEN6,9, LORI LUBIN1, TOMMASO TREU10,11,12, and DENNIS ZARITSKY8

1 Department of Physics, University of California, Davis, CA 95616, USA; marusa@physics.ucdavis.edu
2 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
3 Aix Marseille Université, CNRS, LAM (Laboratoire d’Astrophysique de Marseille) UMR 7326, F-13388 Marseille, France
4 Argelander-Institut für Astronomie, Auf Dem Hügel 71, D-53121 Bonn, Germany
5 Department of Astronomy, University of Florida, 211 Bryant Space Science Center, Gainesville, FL 32611, USA
6 Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, 382 Via Pueblo Mall, Stanford, CA 94305-4060, USA
7 The University of Chicago, The Kavli Institute for Cosmological Physics, 933 East 56th Street, Chicago, IL 60637, USA
8 Steward Observatory, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA
9 Dark Cosmology Centre, Niels Bohr Institute, University of Copenhagen, Juliane Maries Vej 30, DK-2100 Copenhagen Ó, Denmark
10 Department of Physics, University of California, Santa Barbara, CA 93106, USA
11 KITP, Kohn Hall, University of California, Santa Barbara, CA 93106-4030, USA
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ABSTRACT

Spitzer UltraFaint Survey Program is a joint Spitzer and Hubble Space Telescope Exploration Science program using 10 galaxy clusters as cosmic telescopes to study $z \gtrsim 7$ galaxies at intrinsically lower luminosities, enabled by gravitational lensing, than blank field surveys of the same exposure time. Our main goal is to measure stellar masses and ages of these galaxies, which are the most likely sources of the ionizing photons that drive reionization. Accurate knowledge of the star formation density and star formation history at this epoch is necessary to determine whether these galaxies indeed reionized the universe. Determination of the stellar masses and ages requires measuring rest-frame optical light, which only Spitzer can probe for sources at $z \gtrsim 7$, for a large enough sample of typical galaxies.

Our program consists of 550 hr of Spitzer/IRAC imaging covering 10 galaxy clusters with very well-known mass distributions, making them extremely precise cosmic telescopes. We combine our data with archival observations to obtain mosaics with $\sim 30$ hr exposure time in both 3.6 $\mu$m and 4.5 $\mu$m in the central 4’ × 4’ field and $\sim 15$ hr in the flanking fields. This results in $3\sigma$ sensitivity limits of $\sim 26.6$ and $\sim 26.2$ AB magnitudes for the central field in the IRAC 3.6 and 4.5 $\mu$m bands, respectively. To illustrate the survey strategy and characteristics we introduce the sample, present the details of the data reduction and demonstrate that these data are sufficient for in-depth studies of $z \gtrsim 7$ sources (using a $z = 9.5$ galaxy behind MACS J1149.5+2223 as an example). For the first cluster of the survey (the Bullet Cluster) we have released all high-level data mosaics and IRAC empirical point-spread function models. In the future we plan to release these data products for the entire survey.

Key words: dark ages, reionization, first stars – galaxies: clusters: individual – galaxies: high-redshift – gravitational lensing: strong

Online-only material: color figures

1. INTRODUCTION

Spitzer UltraFaint Survey Program (SURFS UP): Cluster Lensing and Spitzer Extreme Imaging Reached Out to $z \gtrsim 7$, 90009; PI: Bradač, co-PI: Schrabback) is a joint Spitzer and Hubble Space Telescope (HST) Exploration Science program. It was designed to image 10 galaxy cluster fields to extreme depths with Spitzer 3.6 $\mu$m and 4.5 $\mu$m bands for 550 hr total. It also includes 13 prime and 13 parallel orbits of HST time for one of the clusters which did not have deep Wide Field Camera 3 (WFC3)-IR and optical HST data (RCS2-2327.4−0204; the rest of the targets have HST data available). Together with the archival data, each field has been or will be imaged with Spitzer for $> 100$ ks (28 hr) per band. Such depths have only been achieved previously with Spitzer observations of the Ultra Deep Field (UDF; Labbé et al. 2013, 2010; González et al. 2010), GOODS (40 hr per field, see below and, e.g., Oesch et al. 2013) and Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDLES) through the S-CANDELS program (PI: G. Fazio; five CANDELS fields to 50 hr depth with IRAC). In the near future, Spitzer Large Area Survey with Hyper-Suprime-Cam Survey (PI: Capak, 90042) will provide 2475h of Spitzer observing over two 1.8 deg$^2$ fields (COSMOS and SXDS); delivering depths of $\sim 10$ hr per pointing. Compared to these studies, SURFS UP has the advantage of studying intrinsically lower luminosities, enabled by gravitational lensing, than blank field surveys of the same exposure time and has been designed to address the two main science goals described below.

1.1. Star Formation at $z \gtrsim 7$

The epoch of reionization marked the end of the so-called “dark ages” and signified the transformation of the universe from opaque to transparent. Yet the details of this important transition period are still poorly understood. A compelling but most likely overly simplistic suggestion is that star-forming galaxies at $z \gtrsim 7$ are solely responsible for reionization. The ability of sources to reionize the universe depends in part

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12 Packard Fellow.
upon their co-moving star formation rate (SFR) density $\rho_{\text{SFR}}$ and star formation history at high redshift (for reviews, see Fan et al. 2006; Robertson et al. 2010; Loeb & Furlanetto 2012). The advent of WFC3 on HST detects these galaxies at rest-frame UV wavelengths (e.g., Ellis et al. 2013; Bouwens et al. 2013; Schenker et al. 2013), while Spitzer observations allow us to trace the rest-frame continuum emission reddenred of 4000 Å (e.g., Labbé et al. 2013). Rest-frame UV and rest-frame 4000 Å data trace two basic properties of stellar populations; the instantaneous SFR dominated by younger stars and the integrated history of the older population, respectively (Madau et al. 1999). The stellar masses allow us to determine the SFR density at $z \gtrsim 7$, which can be compared to the SFR density needed for these sources to reionize the universe (for certain choices of escape and clumping factors; Madau et al. 1999; Robertson et al. 2013; Stark et al. 2013).

SURFS UP has the advantage that by using deep observations of 10 independent sight lines sample variance is reduced compared to, e.g., UDF. Clusters of galaxies, when used as cosmic telescopes, allow us to probe deeper due to high magnification and SURFS UP targets are among the largest galaxy clusters known and were chosen for their extreme lensing strength. This program therefore allows us to push the intrinsic luminosity limits further than the UDF and study representative galaxies at $z \sim 7$ and 8. For example, clusters that are part of this survey have typical magnifications of $\mu \gtrsim 5$, which effectively increases the exposure time by $\sim \mu^2$. For the $z \sim 9.5$ galaxy reported below the intrinsic (corrected for lensing) measured magnitudes in IRAC are $28.6^{+0.9}_{-0.8}$ in 3.6 μm and $27.9^{+0.6}_{-0.4}$ in 4.5 μm, compared to 5σ limiting magnitudes reported by Oesch et al. (2013) in GOODS-N of 27.0 and 26.7, respectively.

One concern, however, when using gravitational lensing is that lensing magnification decreases the effective observing field (as it “enlarges” sources and their separations on the sky). This loss in sky area is more than compensated for by the steep luminosity function (effective slope $> 2$) at the magnitudes that we probe (Bouwens et al. 2012b; Bradley et al. 2012). A second concern is that we need to know the magnification (including errors) of our cosmic telescopes to convert the observed number counts and stellar masses into their intrinsic values. As shown by Bradac et al. (2009), the magnification of well-studied clusters, needed for such conversion, can be constrained using information on distortion and shifts of the background sources to sufficient accuracy. In summary, (1) in the regimes where the luminosity function is steep (effective slope $> 2$), which is true at the magnitudes that we probe) number counts are increased compared to observations in a blank field (i.e., many somewhat fainter galaxies become accessible because of the foreground lens), and (2) magnification errors amount to a smaller error than sample variance when determining the luminosity function at $z \sim 7$. Another advantage of gravitational lensing is that lensed galaxies are often enlarged, easing identification (gravitational lensing magnifies solid angles while preserving colors and surface brightness).

The first demonstration of an established stellar population at high redshift ($z \gtrsim 6$) was accomplished using Spitzer data of the strongly lensed $z \sim 6.8$ galaxy behind A2218 (Egami et al. 2005; Kneib et al. 2004). Detections at 3.6 μm and 4.5 μm allowed the construction of the galaxy’s spectral energy distributions (SEDs) and measurement of the stellar properties. The SED has a significant rest-frame 4000 Å break and therefore indicates that a mature stellar population is already in place at such a high redshift (Egami et al. 2005). These measurements were made possible due to large magnification factors ($\sim 25$). When observing gravitationally magnified objects, Spitzer/IRAC imaging enables us to study stellar populations of the highest-redshift galaxies (see, e.g., Zheng et al. 2012 for a $z \sim 9.5$ galaxy detected by Spitzer; Smit et al. 2013 for detections at $z = 6.6–7.0$).

Considerable investment has recently been made in observing galaxy clusters with HST. The Cluster Lensing And Supernova survey with Hubble (CLASH; Postman et al. 2012) delivered observations of 25 clusters and HST-GO-11591 (PI: Kneib) observed an additional 9 clusters. Future high-redshift exploration will be advanced by the HST Frontier Field (HFF)13 program, a program involving six deep fields centered on strong lensing galaxy clusters in parallel with six deep blank fields (PIs: Mountain, Lotz). Very deep Spitzer data are an excellent complement to deep HST data, which CLASH does not provide. The typical integration times for CLASH clusters prior to SURFS UP range from $\sim 3.5$ hr per IRAC band from the ICLASH program (80168: PI: Bouwens, Bouwens et al. 2012a) to $\sim 5$ hr per IRAC band from the Spitzer IRAC Lensing Survey program (60034; PI: Egami). SURFS UP provides the greater depth and coverage needed in 10 strong lensing clusters specifically chosen for their high lensing strength (see below, 2 of them are part of HFF). The Spitzer campaign covering the HFF will provide similar depth for at least additional two clusters. In summary, Spitzer plays a unique role in the investigation of stellar ages and masses of $z \gtrsim 7$ galaxies. IRAC $3.6 \mu$m and $4.5 \mu$m observation probe rest-frame optical wavelengths ($\sim 0.5 \mu$m) which are the only available data reddenred of rest-frame 4000 Å for these sources and hence can probe presence of evolved stellar populations for a large number of distant sources.

1.2. Evolution of Stellar Mass Function in Galaxy Clusters

With the SURFS UP observations, we will also be able to probe the stellar mass function of $z \sim 0.3–0.7$ members of our cluster sample to depths of $<10^8 \ M_\odot$ (or 0.005 $L_\odot$) for an elliptical galaxy at the highest cluster redshift we probe ($z = 0.7$). This depth far exceeds the current limits from studies of other high-redshift clusters (e.g., Andreon 2006b; Patel et al. 2009; Demarco et al. 2010; van der Burg et al. 2013) and is comparable to the deepest observations of local clusters, such as the Coma cluster and the Shapley Supercluster (Terlevich et al. 2001; Merluzzi et al. 2010). Furthermore, it is comparable to the state-of-the-art stellar mass surveys at low redshifts; e.g., the Galaxy And Mass Assembly survey (Taylor et al. 2011; Baldry et al. 2012), which has limits of $M^* \sim 0.5–1 \times 10^8 \ M_\odot$ at a median redshift of $z = 0.05$. Previous optical/near-infrared (NIR) observations of galaxy clusters at $z \sim 0.8$ suggested a deficit of faint, red galaxies in the cluster red sequence (RS) as indicated by the color–magnitude diagram (CMD) and the RS luminosity function (e.g., De Lucia et al. 2004, 2007; Tanaka et al. 2005; Rudnick et al. 2009; Gilbank et al. 2010; Lemaux et al. 2012). However, other authors find no such deficit (e.g., De Propris et al. 2013; Crawford et al. 2009; Andreon 2006a, 2008). Because rest-frame optical luminosities can be strongly affected by current star formation, color–stellar mass plots can look substantially different than CMDs (e.g., Lemaux et al. 2012). As a result, the stellar mass function and the processes governing its evolution are the most physical and accurate way to trace evolution in the cluster galaxy population. So far, there has been little observed evolution in the cluster stellar mass

13 http://www.stsci.edu/hst/campaigns/frontier-fields/
function; however, published results have only probed down to \(\sim 10^{10} M_{\odot}\) (e.g., Bell et al. 2004; Demarco et al. 2010; Vulcani et al. 2013).

Because evolution is accelerated in overdense environments (e.g., Tanaka et al. 2008), it is essential to probe to lower stellar mass limits in the cluster cores to get a complete picture of galaxy evolution in these regions. SURFS UP will achieve that by making a complete census of star-forming cluster galaxies down to stellar masses of \(10^8 M_{\odot}\) (or \(0.005 L^*\)). Combined with our optical and NIR photometry, IRAC data yield precise stellar masses and their errors (<0.15 dex) for a particular choice of an initial mass function (IMF; e.g., Rowan-Robinson et al. 2008; Swindle et al. 2011). The primary systematic uncertainty is the unknown IMF; for example, changing it from the Chabrier IMF (Chabrier 2003) to the Salpeter IMF (Salpeter 1955) will lead to a shift of \(\sim 0.25\) dex in stellar mass (Swindle et al. 2011). Without the IRAC data, the statistical errors in stellar mass would increase by a factor of two. In summary, IRAC observations allow us to estimate stellar masses for all of our observed galaxies, down to a stellar mass limit comparable to that reached in local clusters (Terlevich et al. 2001; Merluzzi et al. 2010).

This paper describes the survey design, key science goals, and details of reducing the ultra deep Spitzer data. We show the power of SURFS UP to achieve the primary goal listed above by measuring stellar properties for a \(z = 9.5\) galaxy behind MACS J1149.5+2223. In Ryan et al. (2014) we present details of the photometry and measurements of the stellar masses and SFRs for \(z \sim 7\) galaxies behind the Bullet Cluster. The full analysis of all 10 clusters, which will allow us to answer the questions described above, will be presented in subsequent papers after the final data is taken. The paper is structured as follows. In Section 2 we describe the SURFS UP program, in Section 3 we present the data reduction steps. In Section 4 we present the main science goal of the survey. We summarize our conclusions in Section 5. Throughout the paper we assume a \(\Lambda\)CDM concordance cosmology with \(\Omega_m = 0.27, \Omega_{\Lambda} = 0.73,\) and Hubble constant \(H_0 = 73\) km s\(^{-1}\) Mpc\(^{-1}\) (Komatsu et al. 2011; Riess et al. 2011). Coordinates are given for the epoch J2000.0, and magnitudes are in the AB system.

### 2. SURVEY DESIGN AND SAMPLE SELECTION

The survey will use the magnification power of 10 accurately modeled cosmic telescopes to study galaxy populations at \(z \gtrsim 1–10\) with the main focus of studying \(z \gtrsim 7\) galaxies. The clusters were selected based on a number of criteria, listed below.

1. The clusters need to be very efficient lenses (i.e., having significant areas of high magnification). This requires them to have large mass (\(M_{500} \gtrsim 10^{15} M_{\odot}\), see Table 1) and be preferentially elliptical in shape. Furthermore, the critical density \(\Sigma_c\) which relates surface mass density \(\Sigma\) to lensing convergence \(\kappa = \Sigma/\Sigma_c\) is larger at lower redshift, therefore clusters at higher redshifts are likely more efficient lenses. We select clusters whose areas of high magnification are well-matched to both the Spitzer and HST/Advanced Camera for Surveys (ACS) field of view (FOV). Finally, we also want to minimize the obscuration of background galaxies by foreground cluster members. Due to the smaller apparent size and brightness of the cluster members at higher redshifts the ideal redshifts chosen for this survey is around \(z \sim 0.5\).

2. Availability of deep HST ACS and WFC3-IR imaging (for the very efficient lens RCS2-2327.4–0204 where the HST data was not available we obtained the data as a part of this program).

3. Absence of bright stars in the Spitzer FOV (we use Two Micron All Sky Survey—Skrutskie et al. 2006—catalog to check that no stars with K-band magnitude <10 were present near the cluster core).

Much of the work has been done in detecting such population in HST. Surveys of blank fields, in particular HUDF, CANDELS, and the Brightest of Reionizing Galaxies Survey (e.g., Ellis et al. 2013; Schenker et al. 2013; Bouwens et al. 2012b; Oesch et al.

| Target Name | R.A. | Decl. | \(z\) | \(\bar{T}\) (keV) | \(r_{500}\) (Mpc) | \(r_{500}\) (arcmin) | \(M_{500}\) (10\(^{15}\) M\(_{\odot}\)) | \(M^e\) | Total Exp. (ks) | Archive |
|-------------|-----|-------|-----|-----------|-------------|----------------|-----------------|-----|----------|---------|
| MACS0454.1–0300 | 04:54:10.90 | −03:01:07.00 | 0.54 | 7.5 ± 1.0\(^{(a)}\) | 1.31 ± 0.06 | 3.54 ± 0.16 | 1.15 ± 0.15\(^{(1)}\) | 2 | 114 | 24 ks\(^{(b,c,d)}\) |
| Bullet Cluster | 06:58:27.40 | −55:56:47.00 | 0.30 | 11.70 ± 0.22\(^{(b)}\) | 1.81 ± 0.07 | 7.02 ± 0.27 | 2.28 ± 0.28\(^{(1)}\) | 4 | 111 | 22 ks\(^{(b,c,d)}\) |
| MACS0717.5+3745 | 07:17:33.80 | +37:45:20.00 | 0.55 | 12.55 ± 0.70\(^{(a)}\) | 1.69 ± 0.06 | 4.53 ± 0.16 | 2.49 ± 0.27\(^{(1)}\) | 4 | 108 | 18 ks\(^{(b,c,d)}\) |
| MACS0744.8+2927 | 07:44:51.80 | +29:27:33.00 | 0.70 | 8.9 ± 0.80\(^{(a)}\) | 1.26 ± 0.06 | 3.02 ± 0.14 | 1.25 ± 0.16\(^{(1)}\) | 1/2 | 108 | 18 ks\(^{(b,c,d)}\) |
| MACSJ1149.5+2223 | 11:49:53.40 | +22:33:42.00 | 0.54 | 8.7 ± 0.90\(^{(a)}\) | 1.53 ± 0.08 | 4.14 ± 0.22 | 1.87 ± 0.30\(^{(1)}\) | 4 | 108 | 18 ks\(^{(b,c,d)}\) |
| RXJ1347–1145 | 13:47:32.00 | −11:45:42.00 | 0.59 | 10.75 ± 0.83\(^{(b)}\) | 1.67 ± 0.08 | 4.32 ± 0.21 | 2.17 ± 0.30\(^{(1)}\) | 4 | 113 | 23 ks\(^{(b,c,d)}\) |
| MACSJ1423.8+2404 | 14:23:48.30 | +24:04:47.00 | 0.54 | 7.1 ± 0.65\(^{(c)}\) | 1.09 ± 0.05 | 2.95 ± 0.14 | 0.66 ± 0.09\(^{(1)}\) | 1 | 108 | 18 ks\(^{(b,c,d)}\) |
| MACSJ2129.4–0741 | 21:29:26.21 | −07:41:26.2 | 0.59 | 9.0 ± 1.20\(^{(a)}\) | 1.25 ± 0.06 | 3.24 ± 0.16 | 1.06 ± 0.14\(^{(1)}\) | 3 | 108 | 18 ks\(^{(b,c,d)}\) |
| MACSJ2214.9–1359 | 22:14:57.41 | −13:59:22.14 | 0.50 | 8.8 ± 0.79\(^{(a)}\) | 1.39 ± 0.08 | 3.92 ± 0.23 | 1.32 ± 0.23\(^{(1)}\) | 2 | 108 | 18 ks\(^{(b,c,d)}\) |
| RCS2-2327.4–0204 | 23:27:28.20 | −02:04:25.00 | 0.70 | 9.5 ± 1.18\(^{(d)}\) | 1.16\(^{(11)}\) ± 0.08 | 2.78\(^{(26)}\) ± 0.19 | 1.23\(^{(16)}\) ± 0.15\(^{(ii)}\) | 2 | 108 | 18 ks\(^{(b,c,d)}\) |
The sample of galaxy clusters is presented in Table 1. Many of them are merging; this is not surprising as merging clusters have the highest projected ellipticity and hence high lensing efficiency. In particular, high projected ellipticity in the mass distribution generates large critical curves and large areas of high magnifications (Meneghetti et al. 2010). Due to the large number of multiply imaged systems it is usually not more difficult to model the magnification distribution of a merging cluster compared to the relaxed clusters. Finally, we caution that due to the merging nature of many of the clusters the masses quoted in Table 1 might be overestimated; this, however, does not influence the selection as we modeled the magnification distribution separately with the main goal to select the clusters with the highest lensing efficiency within a WFC3-IR FOV.

3. SPITZER DATA REDUCTION AND PROPERTIES

The observations of all clusters were taken in four scheduling blocks, two blocks (separated by ~10° in the roll angle) were followed by two more, separated by ~180° from the previous two to ensure coverage in both channels in the flanking fields. Two pointings (one pointing per band) were sufficient to cover the entire region of high magnification (μ > 2).

Our basic data processing begins with the corrected-basic calibrated data (cBCD). These data include a few IRAC artifact-correction procedures. However, visual inspection of preliminary mosaics illustrates that additional mitigation measures are required. Therefore we applied the warm-mission column pull-down (bandcor_warm.c by M. Ashby) and an automuxstripe correction contributed software (automuxstripe.pro by J. Surace)14 to the individual cBCDs from both channels. These steps produce noticeably improved mosaics, particularly near the cluster core, there are some in the flanking fields.

The process of creating the mosaic images closely follows the IRAC Cookbook15 for the COSMOS medium-deep data; here we describe a few noteworthy exceptions. Like in the Cookbook, all processing from here on is performed with the MOsaic and Point source EXtractor (mopex) command-line tools. The overlap correct is applied to all cBCD frames to bring their sky backgrounds to agreement across the final mosaic (Makozov & Khan 2005). For this correction, we use the DRIZZLE option for interpolation with pixfrac = 1 to fully cover the output pixels. Although this interpolating procedure is considerably slower than others (e.g., spline or bicubic), it produces mosaics with cleaner sky backgrounds. The overlap correction generates temporary files which are used in the next stage of processing.

The two flanking fields are adjacent and aligned with the primary IRAC pointing. Their positions were determined by spacecraft visibility. They typically have only half the number of frames of the primary field. Therefore, we generate two different mosaics per channel. We have typically ~2000 individual frames for the central region, so we use the DRIZZLE algorithm with pixfrac = 0.01 to interpolate the overlap-corrected cBCDs onto the output mosaic. This mosaic results in severe holes and noise along the edges where many fewer frames are available—including the interior edges between the primary and flanking fields. We therefore produce a second mosaic with pixfrac = 0.85, to provide clean images in all connected regions. The former is better for objects close to the cluster core, while the latter is useful when imaging in the flanking fields is required. Both mosaics of the Bullet Cluster are available to the public (see Section 3.3). We will do the same for all reduced data for the remaining nine targets in the future.

We also use the available archival data to produce the final mosaics; for example, the SURFS UP Spitzer/IRAC data for the Bullet Cluster (1E0657−56; Tucker et al. 1995) was complemented with existing data from two programs: 3550 (PI: C. Jones, cryo-mission) and 60034 (PI: E. Egami, warm-mission). For the Bullet Cluster in total there are ~2100 individual frames (per channel), with each having a nominal frame time of 100 s. The final mosaics have a pixel scale of 0.60 pixel−1 (an integer multiple of the HST pixel scale) and have a position angle of CR0TA = 0°. By comparing the Spitzer and HST positions of bright objects we correct for any residual shifts in the relative astrometry (for the Bullet Cluster |Δα, Δδ| = [+0′18, −0′12]), and we subtract it from the CRVAL keywords of the Spitzer images. In Figure 1, we show the false color image using both channels, Figure 2 shows a zoomed-in color map of the Bullet Cluster using Spitzer and HAWK-I K_s band (Clément et al. 2012) with the HST F160W footprint, and Hall et al. (2012) z ~ 7 candidates overlaid.

3.1. Depth and Sky Background

We measure the sky statistics from >50 non-overlapping boxes placed in regions of roughly equal exposure time. These boxes typically contain ~100 pixels and are chosen to be devoid of any objects (or object wings) or significant intra cluster light contribution (the latter is seen as increased background level close to the cluster center). We compute the average sky surface brightness with 4σ outlier rejection separately for each box. We combine the sky-subtracted boxes into a single histogram and add back the global average of the sky surface brightnesses (note that the global background has not been subtracted from the images). In Figure 3 we show the distribution of sky surface brightnesses for both IRAC bands (rows) and

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14 http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysisstools/tools/contributed/mopex/
15 http://irsa.ipac.caltech.edu/data/SPITZER/docs/dataanalysisstools/tools/cookbook/
Figure 1. False color map of the Bullet Cluster data using Spitzer 4.5 μm (red), 4.5 μm + 3.6 μm (green), and 3.6 μm (blue) data as the RGB channels. Areas where only 3.6 μm (4.5 μm) data are available (from earlier programs) are clearly visible in blue (orange). The figure was produced using STIFF (http://www.astromatic.net/software/stiff) and APLpy package (http://aplpy.github.com). This map uses FITS images created with pixfrac = 0.01 (see text).

(A color version of this figure is available in the online journal.)

Figure 2. Zoomed-in color map using Spitzer 4.5 μm, 3.6 μm and HAWK-I Ks band data as RGB channels. Overlaid is the HST F160W footprint (white polygon), and Hall et al. (2012) z ∼ 7 candidates (red circles). The figure was produced following the algorithm from Lupton et al. (2004) and using APLpy package.

(A color version of this figure is available in the online journal.)
Figure 3. Distribution of sky surface brightness for 3.6 μm (top) and 4.5 μm (bottom) data for the Bullet Cluster. In the left column are measurements for the primary, and the right for the flanking field. We have measured the average (μ) and rms (σ) of the sky in non-overlapping boxes obviously free of any objects. The histograms are centered on the average local sky value μ for all realizations (see Section 3.1). It is clear that there is still a very low-level contamination from faint sources, from the positively skewed tail. To estimate the rms, we fit a Gaussian distribution omitting the contaminated region shown in gray.

(A color version of this figure is available in the online journal.)

| Target Name                  | rms 3.6 μm (10⁻³ MJy sr⁻¹) | rms 4.5 μm (10⁻³ MJy sr⁻¹) | PSF FWHM 3.6 μm (pixel) | PSF FWHM 4.5 μm (pixel) |
|------------------------------|-----------------------------|-----------------------------|--------------------------|--------------------------|
| Bullet Cluster               | 0.931                       | 1.04                        | 2.82                     | 2.72                     |
| MACSJ0454.1−0300             | 0.992                       | 1.19                        | 2.76                     | 2.79                     |
| MACSJ0717.5+3745             | 0.957                       | 1.14                        | 2.83                     | 2.83                     |
| MACSJ0744.8+3927             | 0.904                       | 1.09                        | 2.91                     | 2.87                     |
| MACSJ1149.5+2223             | 0.905                       | 1.10                        | 2.76                     | 2.87                     |
| MACSJ1423.8+2404             | 0.757                       | 0.98                        | 2.94                     | 2.91                     |
| MACSJ2129.4−0741             | 0.840                       | 1.05                        | 2.83                     | 2.76                     |
| MACSJ2214.9−1359             | 0.890                       | 1.10                        | 2.83                     | 2.79                     |
| GOODS                        | 0.708^a                     | 1.44^a                      | 2.49                     | 2.46                     |

Note. ^a The GOODS data used for primary field comparison has a depth of 40 hr, we rescaled the rms to 29 hr depth assuming it scales as $\propto \sqrt{t_{\text{exp}}}$. For flanking fields we use GOODS v3.0 public data which have comparable depths.

Calculating the rms sky values in their vicinities. We also compute the rms in a 3″ (radius) aperture on the sky after cleaning the foreground objects. Using rms values, for the Bullet Cluster we achieve 3σ limiting magnitudes of $\sim 26.6$ in 3.6 μm and $\sim 26.2$ in 4.5 μm (the exact value is dependent on the location of the source and is similar for the two methods). Finally, as noted by Ashby et al. (2013), the common practice of basing photometric uncertainties on such noise estimates is problematic, because of a possible residual flux from unresolved sources. By measuring background levels across the mosaic, we estimate the uncertainty due to unresolved sources to be of the order 0.2–0.5 mag. We conclude that the degradation is not significant and is more than compensated by the magnification of the cluster. More discussion of the photometry is presented by Ryan et al. (2014).

3.2. Point-spread Function

For the combined HST and IRAC photometry, we generate empirical IRAC point-spread functions (PSFs) by stacking point sources in the field. We begin with SExtractor (Bertin & Arnouts 1996) tuned to highly deblend these confused IRAC images, specifically DEBLEND_MINCONT = 10⁻⁵. From these catalogs,
we identify stars based on the correlation of FLUX_RADIUS and MAG_AUTO (e.g., Ryan et al. 2011, Figure 2) requiring axis ratio of $b/a \geq 0.9$. We refine the centroids from SExtractor by fitting a two-dimensional Gaussian and align each point source with sinc interpolation. We mask neighboring objects using the segmentation maps from SExtractor grown by 2 pixels in radius. We estimate the flux of each point source after sky subtraction of a sigma-clipped mean and using a circular aperture of 4 pixel radius. At various stages, we reject point sources with bad centroid refinement, too many masked neighbors, or suspect sky levels. Before median-combining the shifted point sources, we normalize their total flux to unity. We median combine the valid sources, and perform a second sky subtraction and flux renormalization. We estimate the FWHM by fitting a Gaussian to the one-dimensional profile. They are listed in Table 2 and are consistent with Gordon et al. (2008). We confirm a subset of point sources that are located in both the HST and Spitzer data (~5 for a typical cluster). Our empirical PSF FWHM values are also in agreement with the values reported in the IRAC handbook (1:66 = 2.77 pixels and 1:72 = 2.87 pixels for 3.6 μm and 4.5 μm respectively). We are releasing the FITS images of the stacked PSF as discussed below.

3.3. Public Data Release

This program will be of use for the broader community for the study of distant, magnified sources and IR properties of lower-redshift galaxies and galaxy cluster members. We have waived any proprietary rights for this program. Furthermore, we are making high-level science products available following publication of the full data set. We are releasing mosaics with two different values of pixfrac = 0.01 and 0.85 for the first cluster. As discussed above, the smaller pixfrac is better for objects close to the cluster core, while the larger one is useful when imaging in the flanking fields is required. We are also releasing the empirical PSF FITS files, because these are needed for joint optical and Spitzer photometry. The data for the Bullet Cluster (and the remaining clusters in the near future) can be found online. We plan to release similar products for all the clusters in the sample.

4. STAR FORMATION AT $z \gtrsim 7$

As mentioned above, the key science goal of SURFS UP is the study of the properties (SFRs and stellar masses) of a representative sample of galaxies. Figure 4 shows five model starburst galaxies with different stellar ages and metallicities. While these galaxies would not be detected in the optical and have similar colors in WFC3/IR bands, they show large differences in the $H_{160W} - [3.6 \mu m]$ and $H_{160W} - [4.5 \mu m]$ colors. The redshift is mostly determined by the detection in the WFC3-IR and non-detection in the bluer bands; Spitzer data is crucial to determine stellar ages and masses. In Ryan et al. (2014) we present the detailed Spitzer photometry and stellar properties for $z$-band dropouts behind the Bullet Cluster from Hall et al. (2012). Here we describe a detection and measurement of the stellar properties of the $z = 9.5$ galaxy behind MACSJ1149.5+2223 (MACS1149-JD) from Zheng et al. (2012).

4.1. Stellar Properties of MACS1149-JD

In addition to the detection in 4.5 μm reported in Zheng et al. (2012), we are also able to report a marginal detection of MACS1149-JD in 3.6 μm (Figure 5). We measure the IRAC fluxes using TFIIT (Laidler et al. 2006), which uses cutouts of each object in the high-resolution, e.g., F160W image, convolves them with PSF transformation kernels (from F160W to 3.6/4.5 μm) to prepare the low-resolution templates, and adjusts the normalization of each template to best match the surface brightness distribution of the IRAC images. Because of the large differences in angular resolution between HST and IRAC PSFs, we use the IRAC PSFs directly as the convolution kernels. To avoid the overcrowded region at cluster centers, we include only objects detected in F160W within a 20′′ × 20′′ box centered at MACS1149-JD. To deal with local sky background, we measure the local sky level around MACS1149-JD within a 48′′ × 48′′ box after masking out the detected sources. We subtract the median value of the sky pixels from the IRAC images and calculate the 1σ deviation as the sky level uncertainty. We then inflate the rms image by the local sky uncertainty, and calculate the magnitude errors from the full covariance matrix of the templates included in the fit. The TFIIT-measured fluxes represent the fluxes within the same isophotal aperture as in F160W ($MAG_{IS0}$ reported from SExtractor).

Finally, we apply an aperture correction of $-0.4$ mag to match our $MAG_{IS0}$ in F160W to the reported total F160W magnitude from Zheng et al. (2012). The IRAC magnitudes measured this way (also listed in Table 3) are $[3.6 \mu m] = 25.7 \pm 0.5$ mag and $[4.5 \mu m] = 25.0 \pm 0.2$ mag, which are in agreement with Zheng et al. (2012). We also list in Table 3 the magnitude errors if the rms images were not inflated by sky level uncertainty, and clearly local sky uncertainty dominates the errors reported by the rms image alone.

Figure 4. Five different spectra for starburst galaxies (from Bruzual & Charlot 2003) redshifted to $z = 8$. The blue curve represents a stellar population at $t = 290$ Myr after the burst, the red and black curve are for $t = 100$ Myr, the green one for $t = 25$ Myr and the cyan for $t = 5$ Myr. All curves are calculated for a metallicity $Z = 0.4 Z_\odot$, except for the black curve where we use $Z = Z_\odot$, and $t = 100$ Myr (to show the effect of metallicity degeneracy with age which is small). Whereas all these galaxies would have similar colors in the HST/ WFC3 bands (blue shaded region, similar spectral slopes within photometric uncertainties), the different ages can be easily distinguished once 3.6 μm and 4.5 μm Spitzer imaging is added (red shaded region), as their $H_{160W} - [3.6 \mu m]$ and $H_{160W} - [4.5 \mu m]$ colors are very different and hence their stellar masses and ages can be determined reliably.

(A color version of this figure is available in the online journal.)

MACS1149-JD in 3.6 μm (Figure 5). We measure the IRAC fluxes using TFIIT (Laidler et al. 2006), which uses cutouts of each object in the high-resolution, e.g., F160W image, convolves them with PSF transformation kernels (from F160W to 3.6/4.5 μm) to prepare the low-resolution templates, and adjusts the normalization of each template to best match the surface brightness distribution of the IRAC images. Because of the large differences in angular resolution between HST and IRAC PSFs, we use the IRAC PSFs directly as the convolution kernels. To avoid the overcrowded region at cluster centers, we include only objects detected in F160W within a 20′′ × 20′′ box centered at MACS1149-JD. To deal with local sky background, we measure the local sky level around MACS1149-JD within a 48′′ × 48′′ box after masking out the detected sources. We subtract the median value of the sky pixels from the IRAC images and calculate the 1σ deviation as the sky level uncertainty. We then inflate the rms image by the local sky uncertainty, and calculate the magnitude errors from the full covariance matrix of the templates included in the fit. The TFIIT-measured fluxes represent the fluxes within the same isophotal aperture as in F160W ($MAG_{IS0}$ reported from SExtractor).

Finally, we apply an aperture correction of $-0.4$ mag to match our $MAG_{IS0}$ in F160W to the reported total F160W magnitude from Zheng et al. (2012). The IRAC magnitudes measured this way (also listed in Table 3) are $[3.6 \mu m] = 25.7 \pm 0.5$ mag and $[4.5 \mu m] = 25.0 \pm 0.2$ mag, which are in agreement with Zheng et al. (2012). We also list in Table 3 the magnitude errors if the rms images were not inflated by sky level uncertainty, and clearly local sky uncertainty dominates the errors reported by the rms image alone.

After performing IRAC photometry, we then perform SED fitting (see Figure 6) using LePhare (Ilbert et al. 2006, 2009;
Figure 5. Object MACS1149-JD from Zheng et al. (2012) shown in combined WFC3-IR colors (left), 3.6 μm (middle), and 4.5 μm (right) in 30″ × 30″ boxes. Bottom row shows IRAC residuals using TFIT (Laidler et al. 2006) after subtracting all nearby objects detected in F160W band (excluding the main object). When performing photometry, all objects (including the main object) are fit simultaneously. North is up and east is left; 30″ corresponds to ∼200 kpc at z = 9.5 and magnification μ = 14.5.

(A color version of this figure is available in the online journal.)

Table 3

| [3.6 μm] | 25.7 ± 0.5 (25.70 ± 0.17 ± 0.49) |
| [4.5 μm] | 25.0 ± 0.2 (25.01 ± 0.078 ± 0.21) |

| Band       | Magnitude |
|------------|-----------|
| F606W      | <28.9b    |
| F814W      | <29.1     |
| F850LP     | <28.1     |
| F105W      | <28.7     |
| F110W      | 27.5 ± 0.3 |
| F125W      | 26.8 ± 0.2 |
| F140W      | 25.92 ± 0.08 |
| F160W      | 25.70 ± 0.07 |

Notes.
a When estimating the magnitude errors we include both the contribution from the statistical error and systematic error due to the uncertainties in the local background error (see Section 4.1). In parenthesis we list these two contributions separately.
b For F160W and all bluer bands we use HST photometry from Zheng et al. (2012). We matched in aperture our measured Spitzer magnitudes, ensuring that colors are measured accurately. For non-detections 1σ detection limits are given.
c Zheng et al. (2012).

Figure 6. SED fit for z = 9.5 MACS1149-JD candidate behind MACSJ1149.5+2223 from Zheng et al. (2012). Here the points show the observed photometry from HST/Spitzer Space Telescope (the upper limits are 1σ), and the line is the best-fit model from Le Phare (including emission lines). On the right vertical axis, we show the intrinsic magnitudes corrected using magnification μ = 14.5.

(A color version of this figure is available in the online journal.)

Arnouts et al. 1999) including fluxes from all available HST and Spitzer filters. The templates we use are from Bruzual & Charlot (2003), but we also add a contribution from nebular emission lines to the templates (see Ryan et al. 2014 for details). This is especially important for an accurate measurement of the SFR and stellar masses using Spitzer bands (Smit et al. 2013). We estimate that MACS1149-JD has a stellar mass of...
\[ M^* = 7^{+1}_{-5} \times 10^8 M_\odot \] (corrected for lensing using magnification \( \mu = 14.5^{+4.2}_{-1.0} \) from Zheng et al. 2012) and an age of \( \sim 450 \) Myr. We report here the best-fit parameters, and the uncertainties which are calculated from the Monte Carlo samples using the methodology described in detail Ryan et al. (2014). We estimate the errors by calculating the rms of the samples. Full results are reported in Table 3. In Figure 7 we show the marginalized probabilities for stellar population parameters. To illustrate the importance of the IRAC data in modeling these galaxies, we show the results without and with the IRAC data. While the photometric redshifts are robust to the exclusion of the IRAC data, the SFRs, stellar masses and ages are not, clearly showing the importance to adding IRAC data.

The fitting results from the full photometry (see Table 3) are broadly in agreement with those best-fit values derived by Zheng et al. (2012). The one possible exception is the mean luminosity-weighted stellar age of MACS1149-JD, which is constrained in Zheng et al. (2012) to be younger than 275 Myr at the 2\( \sigma \) level for the similar set of models that we employ here. In our fitting, both the best-fit model to the observed photometry and the models for more than half of our Monte Carlo realizations have a mean luminosity-weighted stellar age in excess of the 2\( \sigma \) limit derived in Zheng et al. (2012). The difference can perhaps be explained by the additional detection in the 3.6 \( \mu \)m band and the decreased uncertainty in the 4.5 \( \mu \)m band detection, which allows for a more robust measurement of the 4000 Å break. As a result, there exists a hint from our data that MACS1149-JD contains an evolved stellar population\(^{19} \) for its redshift (i.e., >275 Myr), though we cannot definitively rule out younger ages.

4.2. Prospects for Atacama Large Millimeter Array Followup

While Spitzer data increase our confidence in photometric redshift determination of \( z \sim 7 \) sources, the ultimate confirmation will come from spectroscopy. Spectroscopy is hard to do for typically faint high-redshift sources, and it is thus an area where gravitational lensing magnification helps greatly (e.g., Schenker et al. 2012; Bradač et al. 2012). However, despite the magnification, spectroscopic redshifts have been measured for only a handful of sources close to the reionization epoch. The non-detections are interpreted as evidence for the increase in opacity of the intergalactic medium (IGM) above \( z \sim 6 \) (Fontana et al. 2010; Vanzella et al. 2011; Pentericci et al. 2011; Ono et al. 2012; Schenker et al. 2012; Treu et al. 2012, 2013; Finkelstein et al. 2013; if one assumes no evolution in escape fraction and clumping factors between \( z \sim 6 \) and 7).

High ionization and atomic fine structure lines are an alternative way to observe these high-redshift galaxies. Strong \([\text{C}\,\text{ii}]\) emission (rest-frame \( \lambda = 1909 \) Å) is seen in every single lensed galaxy spectrum at \( z \sim 2 \) with stellar masses \( \lesssim 10^8 M_\odot \) and low metallicities (D. Stark 2013, private communication; see also Erb et al. 2006). It is expected that these lines will be present at higher redshifts as well. Another possibility is the \([\text{C}\,\text{ii}]\) line (rest-frame 158 \( \mu \)m). It is the strongest line in star-forming galaxies at radio through far-infrared (FIR) wavelengths and much stronger than the CO(1–0) line (see Carilli & Walter 2013 for a review). By observing \([\text{C}\,\text{ii}]\) emission in \( z \sim 7 \) galaxies we would not only measure their redshift, but also probe the photodissociation region surrounding star-forming regions (Sargsyan et al. 2012). As noted by Carilli & Walter (2013), the interpretation of \([\text{C}\,\text{ii}]\) emission is not straightforward, because \([\text{C}\,\text{ii}]\) traces both the neutral and the ionized medium and it appears to be suppressed in high density regions. Despite these difficulties, however, the \([\text{C}\,\text{ii}]\) line is proving to be a unique tracer of galaxy dynamics in the early universe (see Carilli & Walter 2013 for an excellent compilation of results and references therein).

Using the sample from the first SURFS UP cluster, we now attempt to predict the rest-frame FIR luminosity at \( z \sim 7 \) and the expected \([\text{C}\,\text{ii}]\) flux (for MACS1149-zD the line is unfortunately

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\(^{19} \) The age of the universe at \( z \sim 9.5 \) is \( \sim 520 \) Myr.
outside the current Atacama Large Millimeter Array (ALMA) frequency range). We start by using the lensed (observed) IR luminosity predicted from SED fitting using LePhare (Ilbert et al. 2006, 2009; Arnouts et al. 1999) of the brightest z-band dropout from Hall et al. (2012). The extrapolated IR luminosity for object 3 is \( L_{\text{FIR}}^{\text{lensed}} = \mu L_{\text{FIR}} = 1.2^{+2.4}_{-0.8} \times 10^{12} L_\odot \) (where \( \mu \) is the magnification; \( \mu = 12 \pm 4 \)). Note that there are different definitions of FIR in the literature, for the purpose of this estimate \( L_{\text{FIR}}^{\text{lensed}} \) is defined as integrated luminosity from 8–1000 \( \mu \)m. One caveat is that we determine this luminosity by extrapolating the SED, hence the estimates are highly uncertain.

To determine \( L_{\text{CII}} \) we use the \( L_{\text{CII}}/L_{\text{FIR}} \) luminosity ratio from Wagg et al. (2012). These authors find that the \( [\text{CII}]/\text{FIR} \) luminosity ratio at high redshift is \( 8 \times 10^{-3} \), which is lower than that of the Milky Way; \( 3 \times 10^{-3} \) (Carilli & Walter 2013). Hence we (conservatively) adopt the former. This suggests the [CII] line luminosity of \( L_{\text{CII}} \simeq 10^9 L_\odot \) and translates into a velocity integrated flux of \( 3_{\text{CII}} \Delta v \lesssim 1 \text{ Jy km s}^{-1} \). Such fluxes are easily reachable with ALMA. We caution, however, that this is a rough estimate, as \( L_{\text{FIR}}^{\text{lensed}} \) and the \( L_{\text{CII}}/L_{\text{FIR}} \) luminosity ratio are all very uncertain. Note that the approach we use to estimate flux is different from that used in Ryan et al. (2014), however both yield consistent results. ALMA observations will test these assumptions, and Spitzer data will allow for an efficient selection of sources that will likely show [CII] emission due to a presence of evolved stellar population.

5. CONCLUSIONS

SURFS UP will produce a major advance in our understanding of the formation of the first galaxies, in particular regarding their star formation history and stellar properties. This program will enable us to probe smaller stellar masses (~\( 10^6 M_\odot \)) and specific SFRs (~\( 10^{-8} \text{ yr}^{-1} \)) at the highest redshifts \( z \gtrsim 7 \). If these high-redshift galaxies are responsible for reionization, they need to produce a sufficient number of Lyman-continuum photons in a sustained way. Once these galaxies are identified, the IGM-ionizing photon flux will be estimated from the SFR density, which will include contributions from instantaneous SFR dominated by younger stars and the integrated rate given by the older population (Robertson et al. 2013).

In this paper and in Ryan et al. (2014) we have demonstrated the importance of using IRAC data to estimate stellar masses, ages, and SFRs for \( z \gtrsim 7 \) galaxies. In particular, we have shown that without IRAC data the stellar properties are not robustly determined. At \( z \sim 7 \), the addition of IRAC photometry in SED fitting significantly reduces the biases in the estimated galaxy properties compared to using HST photometry alone (Ryan et al. 2014). At \( z \sim 9 \), the lack of IRAC photometry in SED fitting can even lead to an order-of-magnitude bias in stellar mass, SFR and age estimates. Hence, SURFS UP will contribute significantly to accurate measurements of the stellar mass properties for these galaxies and thus, help constrain the IGM-ionizing photon flux.

Not only do we have a limited knowledge of the earliest formation of galaxies, but our picture of galaxy formation at later times is also lacking many details. The magnifying power of galaxy clusters also allows us to explore otherwise unreachable populations at “intermediate” redshifts (\( 1 < z < 7 \)). We will be able to probe the conditions in typical low-mass, star-forming galaxies at an an epoch when they are otherwise inaccessible. The magnified galaxies provide excellent targets for exploiting the unique capabilities of new facilities like ALMA and James Webb Space Telescope (JWST). By studying galaxy clusters, SURFS UP will also enable measurements of the stellar mass function of \( z \sim 0.3–0.7 \) galaxy cluster members. The survey reaches depths of \( <10^9 M_\odot \) (or \( <0.005 L^* \)) for an elliptical galaxy at \( z = 0.7 \) (our highest-redshift clusters). The large FOV of Spitzer will allow us to study cluster members out to \( R_{\text{vir}} \).

Finally, SURFS UP will be a resource for the broader community for the study of distant, magnified sources and IR properties of lower-redshift galaxies. Data for 9 out of 10 clusters have been taken. We have made available high-level science products (mosaics and empirical PSF measurements) for the Bullet Cluster and we plan on releasing all the data in the near future.

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Facilities: Spitzer (IRAC), HST (ACS/WFC3), VLT:Yepun (HAWK-I)

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