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The Grism Lens-Amplified Survey from Space (GLASS) – XIII. G800L optical spectra from the parallel fields

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ABSTRACT

We present a catalogue of 22 755 objects with slitless, optical, Hubble Space Telescope (HST) spectroscopy from the Grism Lens-Amplified Survey from Space (GLASS). The data cover ∼220 sq. arcmin to 7-orbit (~10 ks) depth in 20 parallel pointings of the Advanced Camera for Survey’s G800L grism. The fields are located 6 arcmin away from 10 massive galaxy clusters in the HFF and CLASH footprints. 13 of the fields have ancillary HST imaging from these or other programs to facilitate a large number of applications, from studying metal distributions at z ∼ 0.5, to quasars at z ∼ 4, to the star formation histories of hundreds of galaxies in between. The spectroscopic catalogue has a median redshift of ⟨z⟩ = 0.60 with a median uncertainty of Δz/(1 + z) ≲ 2 per cent at F814W ≲ 23 AB. Robust continuum detections reach a magnitude fainter. The 5σ limiting line flux is f_{lim} ≈ 5 × 10^{-17} erg s^{-1} cm^{-2} and half of all sources have 50 per cent of pixels contaminated at ≲ 1 per cent. All sources have 1D and 2D spectra, line fluxes/uncertainties and identifications, redshift probability distributions, spectral models, and derived narrow-band emission-line maps from the Grism Redshift and Line Analysis tool (GRIZLI). We provide other basic sample characterizations, show data examples, and describe sources and potential investigations of interest. All data and products will be available online along with software to facilitate their use.

Key words: techniques: spectroscopic – catalogues – galaxies: evolution.

1 INTRODUCTION

The Hubble Space Telescope (HST) provides some of the best ultraviolet (UV) to near-infrared (NIR) imaging available. These data underpin most of our knowledge of the distant Universe. Ground-based spectra – from e.g. VVDS (Le Fèvre et al. 2005), MOSDEF (Kriek et al. 2015), and LEGA-C (van der Wel et al. 2016) – are critical, but the atmosphere limits continuum measurements to the most massive galaxies and blurs all spatial information. Using space-based data reduces these restrictions and yields a cleaner picture of galaxy evolution.

HST’s slitless grisms have played key roles here. They produce maps of every source at every wavelength at spatial scales inaccessible from Earth without adaptive optics. The two NIR grisms – G102 and G141 on WFC3 – have proven especially effective, with e.g. the WISP (Atek et al. 2010) and 3D-HST surveys (Momcheva et al. 2016), and our own Grism Lens-Amplified Survey from Space (GLASS; Schmidt et al. 2014; Treu et al. 2015) providing rest-optical z > 1 spectroscopy over scores to hundreds of sq. arcmin without the need for potentially biasing photometric pre-selection or slit masks. Paired with HST imaging, these data have extended our knowledge of the ages and star formation histories (SFHs) of galaxies at early cosmic times in ways comparable to ground-based results at z ≲ 1 (e.g. Whitaker et al. 2012; Newman et al. 2014; Nelson et al. 2016; Wang et al. 2017, 2019; Abramson et al. 2018; Morishita et al. 2018, 2019).

Beyond their scientific utility, HST’s grisms play a pathfinding role: the astronomical community has decided that space-based, wide-field, slitless spectroscopy will be an increasingly large part

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of its portfolio with the forthcoming operation of JWST, Euclid, and WFIRST. Hence, building intuition, applications, and tools to handle these data is prudent. JWST’s less widely used optical disperser – the ACS G800L grism – is powerful in this context. Covering $\lambda = 0.5$–$1.0\,\mu m$ with $\sim 2.5 \times$ WFC3’s footprint, G800L extends space-based grism surveys to lower redshifts and more than doubles their area. The instrument’s capability has been exploited by the GRAPES (GO9793, PI Malhotra; Pirzkal et al. 2004) and PEARS (GO10530, PI Malhotra; Straughn et al. 2008, 2009) surveys, and 3D-HST, with all results obtained prior to 3D-HST compiled by Kümnel et al. (2011).

Here, we describe GLASS’ use of the G800L grism in parallel observing mode and present a source catalogue covering the 20 fields this survey comprises to 7-orbit depth. These data may be useful to anyone interested in a range of scientific questions – from infalling cluster galaxies at $z \gtrsim 4$ Lyman $\alpha$ emitters – and illustrate what could be done with higher signal-to-noise ratio (S/N) or spectral resolution data from future facilities.

Below, Section 2 describes data acquisition, field locations, reduction procedures, and output products. Section 3 describes the catalogue’s redshift, magnitude, and contamination distributions, and highlights some notable sources for further study. Section 4 proposes some uses of the data, and Section 5 summarizes. We provide file descriptions and some useful pieces of code in the appendix. Throughout, we take ($H_o \, km\, s^{-1} \, Mpc^{-1}$, $\Omega_m$, $\Omega_{\Lambda}$) = (70, 0.3, 0.7) and quote AB magnitudes (Oke 1974). All data/products are available upon request and will be made public.

## 2 DATA

### 2.1 Acquisition

GLASS covers 10 $z \sim 0.4$–0.6 cluster sightlines: six from HFF (Lotz et al. 2017) and four more from CLASH (Postman et al. 2012). WFC3 was placed on the cluster centre at each sightline where gravitational lensing maximizes the chances of detecting high-redshift Lyman $\alpha$ emitters. G102 and G141 were exposed there 6 Cluster Lensing and Supernova Survey with Hubble. Due to CLASH/HFF overlap, eight GLASS sightlines have CLASH coverage.

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$^a$All objects with $c(z – z_{GLASS}) \ll 1$ < 2000 km s$^{-1}$ irrespective of $z_{GLASS}$ where $z_{GLASS}$ is the GLASS cluster redshift from table 1 of Treu et al. (2015).

$^b$Covering band(s) other than F814W to support spectral energy distribution SED (spectral energy distribution) fitting.


$^d$One band.

$^e$Grism data incorporated from GO12099 (PI Riess).

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$^2$James Webb Space Telescope.

$^3$Wide-Field Infrared Survey Telescope.

$^4$Advanced Camera for Surveys

$^5$Hubble Frontier Fields.

$^6$Cluster Lensing and Supernova Survey with Hubble. Due to CLASH/HFF overlap, eight GLASS sightlines have CLASH coverage.
ID assignment, and wavelength calibration. Where possible, one PA was aligned with planned or actual ancillary imaging. This was achieved in 13 fields, where GLASS’ F814W pre-images complement or supplement other HST photometry (Table 1). GLASS pre-images are the only HST images in the remainder (e.g. MACS0717 j0718p3747). We provide example spectrophotometry in Section 4.2 and catalogue matching instructions in Appendix B, but all analyses here including redshift estimation use no additional photometry unless stated.

2.2 Reduction
Although the GLASS NIR data (Schmidt et al. 2014; Treu et al. 2015) were reduced using a modified version of the 3D-HST pipeline (Brammer et al. 2012; Momcheva et al. 2016), the ACS parallel data were extracted using a PYTHON package with improved capabilities: GRIZLI – the Grism Redshift and Line Analysis tool (see Wang et al. 2017, 2019, Brammer 2019). As with the original pipeline, the basic ingredients are two full-field ACS frames: one direct image and one containing the dispersed 2D spectra of all sources therein. The former serves as the reference frame to which the latter is anchored.

GRIZLI first identifies cosmic rays in the F814W and G800L exposures using standard settings with the ASTRODRIZZLE software (Gonzaga & et al. 2012), and fits and removes a two-dimensional master sky image from the grism exposures.8 We refine the astrometric alignment including both a fine relative alignment between exposures and a global alignment to an absolute reference frame, here defined by the Gaia DR2 catalogue (Gaia Collaboration 2018). As there are no telescope offsets between the paired F814W direct and G800L grism exposures, the alignment of the former is applied directly to the latter. Finally, we combine the F814W direct exposures into a rectified mosaic with ASTRODRIZLE at a final sampling of 0.03 arcsec pix−1 and generate a source catalogue and segmentation map from this mosaic using the SEP software package.9

The global contamination model for a given field is constructed in two passes. In the first, we assume that each object has a spectrum flat in units of $f_i$, flux density with a normalization set by its observed flux in the F814W direct image (integrated over the object’s segmentation polygon). In the second pass, we step through objects in the catalogue sorted by increasing magnitude and compute a third-order polynomial fit to each spectrum after subtracting the contamination model from any neighbours (i.e. either the flat spectra of fainter sources or the polynomial models of brighter sources). This refinement is iterated three times. In both passes, the spatial template of the dispersed 2D model spectra is taken from the observed F814W cut-out within an object’s segmentation polygon. Note that this approach neglects morphological variation across the G800L bandpass; e.g. the PSF, continuum colour gradients, and morphological differences between line- and continuum-emitting regions. However, it provides a spatial model with much higher fidelity than any simple parametrized representation (e.g. Gaussian or S´ersic approximations).

The above process automatically yields a source and contamination model for each galaxy detected in the reference image. These can be used to ‘decontaminate’ source spectra – i.e. remove overlapping light from neighbouring sources – to provide more accurate line and continuum characterizations. This was critical in GLASS’ crowded cluster G102 and G141 pointings, but the ACS parallels are sparse enough that source contamination is often negligible (Section 3). Note that no spectra are modelled or extracted for objects not detected in the reference frame. As such, the catalogue presented here is truncated at a F814W flux of $m_{814} = 26$ with various subsamples defined by brighter flux limits (Section 3).

There are two main differences between GRIZLI and the previous GLASS pipeline. First, GRIZLI automatically handles HST grism spectra taken at one or more telescope roll angles that translate into different spectral dispersion PAs. This is implemented in that the 2D spectral models are computed in the pixel space of each separate grism exposure. This is the space in which the field-dependent grism dispersion configuration is measured and defined (e.g. Kümml et al. 2009). This approach allows for evaluating model fits in the space of the original detector pixels with a well-calibrated noise model. Recent works have demonstrated the strengths of this approach (see Morishita et al. 2018a,b; Wang et al. 2019), though note that the GLASS G800L data described here are observed at a single PA. This implementation causes the ACS data format to differ from the WFC3IR data (Schmidt et al. 2014; Treu et al. 2015) in that each field’s 14 subframes are drizzle- and not interlace-combined. All weight maps account for this fact and contain the appropriate pixel-level covariances.

The second difference is that GRIZLI provides automatic redshift estimates of each source, along with its uncertainty, and ‘risk factor’ (Tanaka et al. 2018; proportional to $1/\chi^2$; Section 3). This is done by evaluating fits of galaxy templates similar to those used by the EAZY code (Brammer, van Dokkum & Coppi 2008). At the best redshift – typically where $\chi^2(\zeta)$ is minimized but with an option to include a separate redshift prior – GRIZLI produces measurements and uncertainties of emission-line fluxes and equivalent widths, as well as continuum-subtracted 2D narrow-band maps around the emission-line species. We do not use all of the GRIZLI outputs here, but they may be of value to other investigations.

Note that all of the above processing is based exclusively on the G800L spectra; no ancillary photometry is employed. This caveat should be kept in mind for analyses based solely on our catalogue entries as it affects any quantity that may depend substantially on information outside the grism bandpass, such as stellar mass.

2.3 Products
The GLASS ACS GRIZLI reductions yield a suite of derived data products beyond the reference and spectral data frames:

(i) A master FITS catalogue containing IDs and summary metrics for all extracted sources. Spatial metrics are in pixels at the detection image plate scale of 0.03 arcsec pix−1.

(ii) A ‘.beams.’ FITS file containing 2D cut-outs straight from each grism exposure covering a given object, and the metadata necessary for using them to generate spectral models with GRIZLI.

(iii) A ‘.stack.’ FITS table for each object containing its 2D spectrum, error map, contamination and source models, and F814W...

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7Available at https://github.com/gbrammer/grizli.

8We fit smooth functions to the G800L configuration files provided at http://www.stsci.edu/hst/instrumentation/acs/performance/prism--grism\_wfc-g800l, which are in turn available at https://s3.amazonaws.com/grizli/CONF/ACS/WFC.sky.tar.gz.

9SEP is a PYTHON implementation of the SExtractor software (Bertin & Arnouts 1996) designed to exactly replicate its functionality; https://github.com/kbarbary/sep/
direct image. All are rectified such that the spectral dispersion aligns with the data’s x-axis. Unlike in the .beam files, this rectification (and drizzling) necessitates a resampling of the original detector fits, the best-fitting high-resolution template SED with and without information. −

solution, exposure time, source location, line fluxes, and ancillary information. −

optimal weighting (Horne1986) based on an object’s spatial profile and line emission and continuum models. These extractions use an sensitivity curve [e−optimal weighting (Horne1986) based on an object’s spatial profile and line emission and continuum models. These extractions use an sensitivity curve [e−optimal weighting (Horne1986) based on an object’s spatial profile and line emission and continuum models. These extractions use an sensitivity curve [e−optimal weighting (Horne1986) based on an object’s spatial profile and line emission and continuum models. These extractions use an sensitivity curve [e

3 SAMPLE CHARACTERISTICS

3.1 Counts, quality levels, and depth

GLASS’ G800L spectral data base contains 22 755 objects extracted into three, somewhat overlapping, quality-based subsets defined by continuum and line S/N. These are:

(i) All non-point sources with m814 ≤ 24 or S/Nline ≥ 5 (‘high-S/N + lines’; N = 4636);
(ii) The subset of such galaxies below that subsample’s median GRIZLI zQ (‘low risk’; N = 2319);
(iii) Everything not in (ii) (‘high risk’; N = 20436).

Above, S/Nline refers to the S/N in any of the following features as identified by GRIZLI: Hα, Hβ, [O II], [O III], [S II], [Mg II], or Lyα. The magnitude cut corresponds roughly to the inferred 5σ continuum sensitivity – ~ 5 × 10−19 erg s−1 cm−2 Å−1 (Fig. 1) – as measured in a 1 arcsec spatial aperture. ‘zQ’ is the GRIZLI-characterized redshift quality/risk (lower is better), which correlates well with redshift errors estimated as Δz ≡ 84th−16th P(z) percentile. Fig. 2 shows P(z) PDFs for each quartile of the zQ distribution.

There are low risk sources with no detected emission lines. These are ~1 mag brighter on average than the full low risk sample –

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Figure 3. The redshift (left) and redshift uncertainty (right) distributions for the GLASS G800L sample. Here and in all following plots, the ‘high’ and ‘low risk’ samples are plotted in red and blue, respectively. These are defined based on the median $z_Q$ of all sources with $m_{814} < 24$ or $S/N \geq 5$, whose distributions are plotted in gold. The median redshift for those sources is $\langle z \rangle \simeq 0.60$, with the low risk sample at $\langle z \rangle \simeq 0.58$. Median formal uncertainties rise from $< 1$ per cent for low risk to nearly 50 per cent for high risk objects. Half of the full sample has $\Delta z/(1+z) \lesssim 0.35$. These uncertainties would be reduced by the addition of archival photometry where available, especially at $m_{814} \gtrsim 23$ (Table 1, Fig. 5).

Figure 4. Left: GLASS G800L GRIZLI redshifts compared to those from VLT VIMOS as taken by various authors (see the text). Agreement is quite good at $z < 1$, with the global sample biased to lower redshifts by just $\mu(\Delta z) = -0.01$ with a scatter, $\sigma_z$, of the same order (right-hand panel). A similar comparison with HFF photo-$z$s is presented in the appendix. Based on this comparison, the catastrophic outlier fraction is $62/131 = 0.47 \pm 0.09$ and $21/56 = 0.38 \pm 0.13$ for all sources and those with GLASS-detected emission lines, respectively. ‘Catastrophic’ is defined as $\Delta z > 3\sigma_z$ for the full sample (black histogram at right).

$m_{814} = 22.55$ versus 23.50, respectively – corresponding to the mean increase in continuum quality needed to achieve the redshift precision otherwise supplied by lines. Of course, ‘low risk’ does not imply no risk, and the spectra of any (set of) high-interest object(s) should be vetted depending on usage.

Fig. 3 shows the sources’ inferred redshift distribution (left) and redshift error distribution (right; $\equiv \Delta z/(1+z)$). Note that, due to the inclusion of template lines spanning $\text{[OII]} \lambda 3727$ and redward, there is an artefact in the redshift distribution at $z \sim 1.7$ where that feature drops out of the G800L bandpass. The sample’s median redshift is $z \simeq 0.60$, irrespective of quality cuts. Compared to the high risk subsample, the enhanced quality of the other objects’ redshifts is clear, with the $\sim 2200$ low risk systems having estimates formally precise to $< 1$ per cent. Visual inspection of high-quality objects suggests these redshifts are systematically accurate to within the $2\sigma$ formal uncertainties. The $R \sim 40$ spectral resolution makes more quantitative cross-checks difficult, but comparisons to much higher resolution VLT VIMOS spectra for 131 common objects suggest agreement is at the $\Delta z = 0.01$ level in the median, with a scatter of $\sigma_z = 0.01$ below $z = 1$ (Fig. 4; data from Grillo et al. 2016; Caminha et al. 2017; Karman et al. 2017; Monna et al. 2017). Fig. 5 illustrates that this quality is typical at $m_{814} \lesssim 22$ ($S/N \sim 20$ per spectral pixel), and true for at least 50 per cent of objects up to a magnitude fainter.

The left-hand panel of Fig. 6 shows the $F814W$ apparent magnitude distribution for the above samples. Half of the full sample is brighter than $m_{814} \approx 25$, though it is dominated by insecure redshifts at that limit. The distribution of ‘high-$S/N$ + lines’ objects cuts off sharply at $m_{814} = 24$ by construction (see definition above), though counts in the low risk subsample remain relatively flat beyond this point. Comparing these histograms amplifies Fig. 5’s results, suggesting that robust automated redshift estimations probably require ancillary SED information or spectral lines beyond $m_{814}$.

11Available at https://sites.google.com/site/vltclashpublic/data-release.
Fig. 5. GLASS G800L GRIZLI redshifts are precise to < 1 per cent at \(m_{814} \lesssim 22\) for most sources but degrade rapidly by \(m_{814} \sim 24\), where ancillary SED coverage or strong emission lines are needed to ensure fidelity. The coloured lines show redshift uncertainty quartiles as a function of flux, \(\sim 22\) in these data, so catalogue values should be used cautiously. Inverted, this statement provides a selection criterion, such that GLASS sources with \(m_{814} > 22\) and tight redshift distributions are probably high-EW line emitters.

The right-hand panel of Fig. 6 presents the samples’ rough stellar mass (\(M_*\)) limit. For the low risk objects, this extends from \(\log M_*/M_\odot \sim 7 \at z \sim 0.6\) to \(\log M_*/M_\odot \sim 9 \at z \sim 1\) – similar to the main GLASS catalogue limits (Morishita et al. 2017). We caution, however, that these estimates are based only on the information in the G800L spectrum and therefore may change significantly when ancillary photometry is included in the inference (Section 4.2).

Of course, all of the above depends fundamentally on the grism S/N. The top panel of Fig. 7 shows the median per-pixel S/N for the full sample (grey) and the baseline quality cut (\(m_{814} \leq 24\) or any line detected at \(>5 \sigma\)). In the case of the former, half of the spectra have \(S/N > 2 \mathrm{pix}^{-1}\), and 25 per cent have at least twice that. The high-confidence sample has a median and upper quartile of \(\sim 7\) and \(\sim 20\), respectively, more than triple the \(S/N\) of the general population. We therefore recommend basing most general analyses on at least our ‘high-S/N + lines’ quality cut, and only proceeding beyond this after more rigorous exploration of the data. Fortunately, Fig. 7’s middle and bottom rows reveal that contamination is often not an impediment: half the sample has > 50 per cent of pixels free of any contamination. Alternatively, half of sources have \(\lesssim 20\) per cent of pixels contaminated at \(>20\) per cent. Contamination (by either metric) is slightly higher for the higher quality data subset. This is likely due in part to their typically \(\sim 30\) per cent larger half-light radii (Fig. 8), which increases the probability of spectral collisions.

3.2 Higher level outputs: spectral line maps

The GLASS G800L catalogue contains automated spectral line identifications. The left-hand panel of Fig. 9 shows the distribution of galaxy fractional counts as a function of the number of lines detected at \(S/N_{\text{line}} \geq 5\) and quality cut. The corresponding line IDs for the low risk sample are shown at right. Equation (1) characterizes the magnitude and wavelength dependence of the fifth percentile line flux for these objects:

\[
\log f_{0.05} = -9.78 - 12.81 \lambda + 6.28 \lambda^2 - 0.04 M - 0.06 M \lambda + 0.01 M^2,
\]

where \(\lambda \equiv \lambda/7200 \; \text{Å}\) and \(M \equiv m_{814} - 23\) for \(5000 \leq \lambda/\text{Å} \leq 10000\) and \(20 \leq m_{814} \leq 26\).

As expected, the higher quality samples typically have one to two well detected lines while the general population has zero. Of detected lines, the most common are [O II], [O III], and the strong Balmer lines. However, even at moderate \(S/N_{\text{line}}\), these IDs should be treated with care: visual inspection suggests \(\sim 20\)–\(40\) per cent of sources at fixed \(N_{\text{lines}} \in [1, 3]\) may reflect spurious characterizations. Furthermore, because [Mg II] is not explicitly included in the fitting templates – fluxes are simply measured at the relevant wavelength given the redshift inferred from the continuum + [O II] \(\lambda 3727\) and redder emission lines – objects identified as [Mg II] emitters mainly reflect reduction errors or noise spikes. Hence, these sources should not be taken \textit{prima facie} as e.g. AGN or Lyman continuum leaker candidates (Finley et al. 2017; Henry et al. 2018). Appendix B contains example code to extract high confidence line emitters.

In addition to the total fluxes and errors for every line in every source, GRIZLI outputs 2D spectral cut-outs in the relevant wavelength regions. Fig. 10 shows examples of these line maps for two high-quality sources with their direct images and full 1D and 2D spectra. The source on the left is a typical \(z \sim 0.2\) star-forming galaxy with prominent and extended H\(\alpha\). The source on the right is a high-EW [O III] emitter at \(z \sim 0.65\) with quite different oxygen

Figure 6. \(F814W\) magnitude distributions (left) and estimated stellar mass coverage as a function of redshift (right) for the full and quality-defined samples. Colour coding is as in Fig. 3. Sources in the low risk sample fainter than \(m_{814} = 22\) tend to be high-EW line emitters. Lines therefore form the basis of redshifts in that regime, with the continuum shape playing a larger role for brighter objects. High-quality sources reach \(\log M_*/M_\odot \sim 7\) and \(\sim 9\) at \(z = 0.60\) and 1.0, respectively, though these numbers are based on the relatively small G800L bandpass.
Figure 7. Top: median S/N per spectral pixel from the optimal 1D extractions for all galaxies (grey) and those in the high-S/N + lines subsample (gold). The latter has about 3 × the S/N as the former. Middle: the fraction of source 2D spectral pixels whose flux is contaminated by overlapping traces to at least 20 per cent. Unlike in the WFC3 data, fully half of G800L GLASS spectra have fewer than 20 per cent substantially contaminated pixels. Bottom: median contaminating flux per pixel per source; another metric of contamination. Cumulative distributions for all quantities are shown at right: 75 per cent of objects have a median per-pixel contamination of < 20 per cent; 75 per cent of high-S/N + lines objects have typical continuum S/N > 40.

3.3 Notable sources

Slitless spectroscopy avoids the need for photometric pre-selection. As such, it maximizes the chance of serendipitously capturing interesting sources. Fig. 11 shows two of these in the GLASS G800L footprint that are also known redshift misclassifications (due to the modelling of lines only at and blueward of [O II] λ3727 in the template spectra; see Section 3.1). As revealed by its prominent Ly α, carbon lines, and point-like morphology, the source at left is a z ~ 4 quasar. Of course, GLASS data simultaneously provide a redshift survey along this QSO’s line of sight, and thus immediately suggest 61 (164) foreground candidates with a ρ ≤ 150 (300) kpc impact parameter from the quasar suitable for characterizing H I and low-ionization species such as Mg II (Chen et al. 2010; Prochaska et al. 2011; Rudie et al. 2012; Johnson, Chen & Mulchaey 2015). As such, this source could support higher resolution spectroscopic follow-up to learn about the circumgalactic media (CGM) of scores of galaxies (though 30-m class facilities will be needed for R ~ 40 000 studies). Combined with their ISM maps (Fig. 10), the CGM enrichment levels/temperatures/ionization states derived from such follow-up could provide powerful empirical constraints on metal transport, and therefore evolutionary models (e.g. Davé, Finlator & Oppenheimer 2011; Peeples et al. 2014; Muratov et al. 2015; Davé et al. 2017). Both of these studies are enabled by slitless spectroscopy.

Figure 8. Sample size distribution. The high-S/N + lines sample comprises larger sources on average, contributing to their slightly higher contamination levels.

Figure 9. Line detection statistics for all galaxies and quality subsamples split as in Fig. 3. Line IDs from the low risk sample cut (blue histogram at left) are shown in the right-hand panel. All lines have integrated S/N ≥ 5. Unsurprisingly, higher quality subsamples tend to have more high-confidence line detections, with the mode in the full and high-risk samples being zero lines. Of detections, the most common is [O III]. Note that low risk sources with no detected lines are on average ~1 mag brighter than the full low risk sample (m814 = 22.55 versus m814 = 23.50, respectively), corresponding intuitively to the fact that their continuum must be better measured to ensure such a high-quality redshift solution. Note also that, since the line is not explicitly modelled, sources identified as [Mg II] emitters typically reflect reduction errors or noise spikes.
telescopes for similar integration times, albeit at lower spectral resolution (Steidel et al. 1999; Shapley et al. 2003).

4 DISCUSSION AND FURTHER APPLICATIONS

The GLASS G800L data base will support a range of investigations. We note three potentially fruitful avenues below beyond the QSO and LBG follow-up studies just discussed.

4.1 Infalling cluster members

As shown in Table 1, each pointing in the catalogue contains ∼20–40 objects within 2000 km s⁻¹ of the HFF or CLASH cluster redshifts. These are likely galaxies either falling into the cluster potential for the first time, or ‘splashing back’ after one or more crossings through the clusters (More, Diemer & Kravtsov 2015; Baxter et al. 2017). Both cases present opportunities to study the forces affecting galaxies in the densest environments in the Universe. We encourage anyone interested in ram pressure stripping (Gunn & Gott 1972) or pre-processing (Zabludoff & Mulchaey 1998) to explore these objects. Analogous analyses to Vulcani et al. (2015, 2016, 2017, see Section 4.3) but based on [O iii] may, for example, prove powerful.

4.2 Joint analyses with HST photometry

Over half of the sources in the data base lie in regions covered by CLASH, HFF, or other HST imaging. Given the limited bandpass of the G800L grism, incorporating these data into any further SED fitting is valuable, especially for analyses that rely on accurate stellar mass or SFR inferences. Fig. 12 shows the GLASS spectra overlaid on HFF photometry for three of the 859 common GLASS/Shipley et al. (2018) sources in the Abell 2744 parallel field. For low risk sources, fluxing between the grism data and HFF photometry is good to \( \Delta m_{14} = 0.1 \) mag (such that HFF fluxes are brighter) with a scatter of 0.25 mag about that offset.\(^\text{12}\) The grism-derived continuum SED model extrapolated well outside the G800L bandpass can be predictive to similar levels – low risk median \( m_{GRIZLI} - m_{HFF} = [0.19, 0.25, 0.25, 0.25] \) in [F105,125,140,160W] with >0.5 mag

\(^{12}\)This measurement accounts for zero-point and Milky Way extinction, but not aperture corrections, to the HFF data.
Figure 12. Examples of GLASS G800L spectra (blue) and GRIZLI inferred continuum SEDs (grey) shown with matched source photometry from the HFF campaign (Shipley et al. 2018, orange circles). Some inferences agree remarkably well with photometry lying well outside the grism bandpass despite its limited coverage; others are less consistent. Such offsets – typically at the ~0.25 mag level (Section 4.2) – will affect stellar mass and SFR estimates. However, the consistent location of observed and inferred features (e.g. the 1.6 μm bump) support the accuracy of these sources’ grism-determined redshifts (see also Fig. C1). These data are available to anyone wishing to perform joint spectrophotometric SED fitting on the 13 fields where HST photometry exist (Table 1). More examples of low risk objects in the HFF footprints are shown in Appendix D.

scatters around these offsets – but larger disagreements in the IR and UV can obviously occur.

Moreover, the combination of low-resolution grism spectroscopy covering, e.g. the Balmer or 4000 Å breaks with broad-band photometry to the red and blue is now being used to great effect covering, e.g. the Balmer or 4000 Å breaks with broad-band and UV can obviously occur.

Figure 12. Examples of GLASS G800L spectra (blue) and GRIZLI inferred continuum SEDs (grey) shown with matched source photometry from the HFF campaign (Shipley et al. 2018, orange circles). Some inferences agree remarkably well with photometry lying well outside the grism bandpass despite its limited coverage; others are less consistent. Such offsets – typically at the ~0.25 mag level (Section 4.2) – will affect stellar mass and SFR estimates. However, the consistent location of observed and inferred features (e.g. the 1.6 μm bump) support the accuracy of these sources’ grism-determined redshifts (see also Fig. C1). These data are available to anyone wishing to perform joint spectrophotometric SED fitting on the 13 fields where HST photometry exist (Table 1). More examples of low risk objects in the HFF footprints are shown in Appendix D.

such an analysis, but were limited to just four systems due to the high contamination rates in GLASS’ central WFC3 pointings. The G800L data do not suffer from this issue, so spatially resolved spectrophotometric SFH reconstructions based on functional [e.g. by PSYSPECFT (Newman et al. 2014), or other means (Iyer & Gawiser 2017)] or free-form inferential techniques (Pacifici et al. 2012; Kelson et al. 2014; Leja et al. 2017; Morishita et al. 2018b) should yield a valuable data base of hundreds of high-quality mass, SFR, and structural histories over large ranges in observed mass, SFR, and structural parameters.

4.3 Emission-line mapping

As mentioned in Sections 1 and 3.2, Fig. 10 illustrates one of the key advantages of HST and future space-based slitless spectroscopy: the automatic production of spatially resolved spectral features mapped at the diffraction limit ~ 600 pc at z = 0.6 (FWHM = 0.09 arcsec). These maps can be used, for example, to infer galaxy metallicity distributions and even outflow patterns at sub-kpc scales to challenge numerical feedback and star formation models in new ways. For example, Vulcani et al. (2015, 2016, 2017) used the G102 Hα maps from GLASS’ central pointings to study the connection between galaxy stellar and gas morphology, and associate this with various features of the local and global environment in clusters. Jones et al. (2015) and Wang et al. (2017) used oxygen and Hβ to produce gas-phase metallicity maps and gradients for sources at z ~ 1–3 and unprecedentedly low stellar masses (log M∗ ≤ 8). Wang et al. (2019) identified two such sources with steeply positive gradients ([O II] ∝ r) and used simple models to produce outflow maps and mass loading factors as a function of underlying stellar mass density, showing that individual systems are not described well by only energy- or momentum-driven wind models. The GLASS G800L data will support similar studies based on [O II] through Hα lines at z ≤ 1, both outside and in the infall regions around massive clusters. Further two-dimensional explorations of the ISM will no doubt be fruitful.

5 SUMMARY

We present a catalogue of 22 755 objects with ACS G800L slitless spectroscopy from the 20 GLASS parallel fields (Table 1). The catalogue extends to mB14 = 26 with uniform 7-orbit (~10 ks) coverage over ~220 sq. arcmin. Sources have a median redshift of z = 0.60 with median uncertainties of Δz/(1 + z) ≤ 0.02 at mB14 ≤ 23 (Figs 3 and 5) and are typically contaminated at the 0 per cent–20 per cent level (Fig. 7). About a quarter of the sample either has continuum flux detected at ≥5σ (mB14 ≲ 24; fL ≈ 5 × 10−19 erg s−1 cm−2 Å−1) or S/N ≥ 5 in at least one spectral line (fL ≈ 5 × 10−17 erg s−1 cm−2) such that median redshift errors are ~1 per cent. Incorporating photometry for the 13 fields that overlap with extant HST imaging from CLASH, HFF, or other programs will allow redshifts to be obtained to much greater depth and support a rich variety of spectrophotometric studies into galaxy SFHs at z ~ 0.5–1.5 (Section 4.2).

The full catalogue also contains full 2D spectra, contamination, and source models for each object, along with automated line identifications, fluxes, uncertainties, and 2D spatially resolved maps produced by GRIZLI. Optimal 1D extractions are also provided, as are full UV–sub-mm best-fitting SEDs and redshift PDFs. All data and derived products are available on request, and will be published on MAST along with code for performing various basic operations – which we also give here in Appendix B.
These data and products will support a wide range of investigations – from mapping galaxy outflows at $z < 0.8$ (Sections 3.2 and 4.3) to identifying QSOs and LBGs at $z \sim 4$ (Section 3.3) – and serve as useful intuition builders as the field prepares for the increasing ubiquity of slitless spectroscopy in the eras of JWST and WFIRST.

Facilities: HST ACS.

Software: IDL (Coyote libraries; http://www.idlcoyote.com/), PYTHON (GRIZLI).

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APPENDIX A: FILE NAMES, FORMATS, AND CONTENTS

The core component of the GLASS G800L data base is the catalogue master FITS table:

`i glass-acs-2019.05.10.fits`

This table contains field names and IDs for all extracted sources – from which their data filenames can be constructed – along with a wealth of summary metrics described at the end of this appendix.

The master FITS file is designed for the data base’s organization into 20 folders – one for each ACS pointing. These are named by their field centroid coordinates in the format:

`i j<RRAA>_{mDEDE}`

such that ‘j0014m3023’ corresponds to the Abell 2744 parallel at PA 323.13 These correspond to the `ROOT` column in the master catalogue. Within each folder, all objects are identified by a source

13 A program to translate these coordinates to a cluster field name is available on request and will be posted to the MAST website.

Downloaded from https://academic.oup.com/mnras/article/493/1/952/5721532 by Danish Regions user on 07 December 2020
number, corresponding to the ID column. As such, the master catalogue can be used to point to the ii-th object’s data files by writing:

| folder = mastercat[[ii]].ROOT  |
| sourceID = string(mastercat[ii].ID, f = ‘(FITS)’) |
| sourceFileBase = folder+’/’+folder+’_’+sourceID |

which will construct the base filename from which a source’s data files are built (Appendix B).

A1 Individual source files

As mentioned in Section 2.3, each source is associated with multiple data files. These are defined by the following suffixes appended to their base ID jRARA[n].DEDE_0IDID:

(i) ‘.stack.fits’ – A nine layer 2D FITS table containing:

(a) SCI – A source’s rectified, drizzled 2D spectral cut-out;
(b) WHT – inverse variance array;
(c) CONTAM – contamination model;
(d) MODEL – source model;
(e) KERNEL – F814W direct image used to convolve the 2D trace to a common spatial sampling.

Layers 1, 2, 4, and 5 are then repeated with the source resampled to a common PA. Since each GLASS source is observed only once, this PA is set to the PA of observation, such that the layers are identical (to <1 per cent). This file’s header also contains the wavelength solution, exposure time, RA/Dec., and other ancillary information.

(ii) ‘.full.fits’ – An N ≥ 5 layer 2D FITS table containing:

(a) ZFIT_STACK – A six-column table containing redshift estimation information. This includes the ZGRID redshift array, P(z) distribution (PDF), redshift RISK and CHI2 goodness of fit distributions, and SED template/redshift covariance matrix (COVAR);
(b) COVAR – Covariance matrix of the template fit coefficients at the best-fitting redshift (taken to be where P(z) is maximized from the previous extension).
(c) TEMPL – A three-column table containing the best-fitting SED (FULL), continuum-only model (CONTINUUM), and wavelength array spanning 0.02 < λ/μm < 2 × 10⁴ (WAVE);
(d) DSCI – F814W source direct image sampled at 0.1 arcsec pix⁻¹;
(e) NWHT – F814W image weight map sampled at 0.1 arcsec pix⁻¹;
(f) LINE001 – Map of LINE001 in the file header;
(g) CONTINUUM – Continuum near LINE001 in the file header;
(h) CONTAM – Contamination near LINE001 in the file header;
(i) LINWHT – Weight map near LINE001 in the file header;
(j) LINE002 – As above, but for LINE002 in the file header;

Layers 6–N will not be present in an object with no entries in the master catalogue’s HASLINES column (see below) or no lines in this file’s header. Otherwise, e.g., Hαβγδ, [O II] and [O III], [S II] have names ‘Ha, Hb, Hg, Hd, O II, O III, S II,’ etc. There is one set of four layers for each line. The header also contains the wavelength solution, exposure time, RA/Dec., line fluxes, and other ancillary information.

(iii) ‘.1D.fits’ – A six-column 1D FITS table containing:

(a) WAVE – Wavelength array spanning only the G800L bandpass (5450 < λ/Å < 10 170);
(b) FLUX – Optimally extracted, contamination-subtracted 1D source spectrum (e⁻¹ s⁻¹);
(c) ERR – 1σ noise on FLUX (e⁻¹ s⁻¹);
(d) FLAT – Sensitivity curve needed to transform the above into f (e⁻¹ s⁻¹ erg s⁻¹ cm⁻² Å⁻¹);
(e) LINE – Best-fitting galaxy SED template, including emission lines.
(f) CONT – Best-fitting galaxy SED template, continuum only.

Note that the spatial sampling in these files is 0.1 arcsec pix⁻¹ rather than the detection images’ 0.03 arcsec pix⁻¹.

The getfname function in Appendix B returns the filenames for the above FITS tables given a source’s ROOT and ID entry in the master catalogue.

A2 Master catalogue column definitions

The following entries are found in the GLASS G800L master catalogue FITS table:

1 ROOT – ACS field (string)
2 ID – Source ID in ROOT (int)
3 RA – Source RA (J2000, decimal deg.; double)
4 DEC – Source DEC (J2000, decimal deg.; double)
5 NINPUT – N frames in source’s G800L coadd (int; 1–14)
6 REDSHIFT – Source redshift estimate (z_MAP; float)
7 NUMLINES – Number of potential lines in source spectrum (int; 0–10)
8 HASLINES – Emission-line IDs (string; space-separated)
9 CHI2POLY – χ² of a third-order polynomial fit to the spectrum (float)
10 DOF – Approximate spectral degrees of freedom given by the total number of unmasked pixels in the ‘beams’ spectra extracted from the grism exposures (float)
11 CHIMIN – Minimum χ² of the SED template fit on a redshift grid (float)
12 CHIMAX – Maximum χ² of the SED template fit on a redshift grid (float)
13 BIC_POLY – ‘Bayesian Information Criterion’ of the polynomial fit: ln(DOF) · k + (CHI2POLY – CHIMIN), where k = 4 + N₈ and N₈ is the number of spectra in the .beams file, since an additive background component is fit for each.
14 BIC_TEMP – Bayesian Information Criterion of the template fit, where k = N₆ + N₈ and N₆ is the number of non-zero template fit coefficients.
15 BIC_DIFF – Difference BIC_POLY – BIC_TEMP. Large values generally correspond to cases where the galaxy SED templates much better explain the observed spectrum than the trivial polynomial fit.
16 Z02 – 2σ redshift lower limit (float)
17 Z16 – 1σ redshift lower limit (float)
18 Z95 – 50 per cent confidence redshift estimate (float)
19 Z84 – 1σ redshift upper limit (float)
20 Z97 – 2σ redshift upper limit (float)
21 ZWIDTH1 – 1σ Δz (84 – 16; float)
22 ZWIDTH2 – 2σ Δz (97 – 2; float)
APPENDIX B: USEFUL ALGORITHMS

Below are some useful IDL routines to perform some basic data operations mentioned in the main text.

B1 Return the high S/N + lines and low/high risk subsamples:

```idl
function getGoldSample, mastercat, $ MAGLIM = maglim, $ SNLIM = snlim
if NOT keyword_set(MAGLIM) then maglim = 24.
if NOT keyword_set(SNLIM) then snlim = 5.

;; Define 'high S/N + lines' objects
hiQ = where(mastercat.MAG_AUTO le maglim OR $ mastercat.SN_HA ge snlim OR $ mastercat.SN_HB ge snlim OR $ mastercat.SN_GII ge snlim OR $ mastercat.SN_OIII ge snlim OR $ mastercat.SN_SII ge snlim OR $ mastercat.SN_MGII ge snlim OR $ mastercat.SN_LYA ge snlim) AND NOT $ mastercat.IS_POINT, compl = hiQ)
```

B2 Match to HFF photometry from Shipley et al. (2018):

```idl
function loadHffPhot, hffPhotFile

;; Restore the Shipley et al. .save.catalog
restore, hffPhotFile
minds = n_elements(ra)

;; Find the NIR intrument
if n_elements(fKS_HAWKI) gt 0 then begin
  fks = fKS_HAWKI
eks = eKS_HAWKI
  flgks = redflag.KS_HAWKI
endif else begin
  fks = fKS_MOSFIRE
eks = eKS_MOSFIRE
  flgks = redflag.KS_MOSFIRE
endif

;; Create the SED, error, and flag arrays
;; (F435W--Spitzer, 4.5 um)
fluxes = transposed([fF435W, [fF606W], [fF814W], [fF165W], [fF192W], [fF235W]])
errs = transposed([eF435W, eF606W, eF814W, eF165W, eF192W, eF235W])
:: Add the MK dust and zeropoint corrections
:: (should they be necessary; key names differ
:: slightly between catalogues)
mwcorr = transpose([[nw.F435W], [nw.F606W],
                   [nw.F814W], [nw.F105W], [nw.F125W], [nw.F140W],
                   [nw.F160W], [0.0], [1.0], [1.0]])
if N_ELEMENTS(zpcorr_F814W) gt 0 then $
  zpcorr = transpose([[zpcorr_F435W], [zpcorr_F606W],
                       [zpcorr_F814W], [zpcorr_F105W], [zpcorr_F125W],
                       [zpcorr_F140W], [zpcorr_F160W], [0.0], [1.0], [1.0]])
else $
  zpcorr = transpose([[zpcorr_F435W], [zpcorr_F606W],
                       [zpcorr_F814W], [zpcorr_F105W], [zpcorr_F125W],
                       [zpcorr_F140W], [zpcorr_F160W], [1.0], [1.0], [1.0]])$
endif
:: Set up the output
nbands = n_elements(fluxes[*,$0])
results = [LAMBD[1:4350, 6000, 8140, 10500, 12500, 14000, 16000, 22500, 35000, 46000]], SED : flirtarr(nbands), $
ESED : flirtarr(nbands),$
FLAGS : bytarr(nbands),$
RA : 0.d,$
DEC : 0.d,$
MCORR : flirtarr(nbands),$
ZPCORR : flirtarr(nbands),$
results = replicate(results, ninds)
:: Fill the output structure
:: get fluxes to erg/s/cm^2/Hz
minds = n_elements(ra)
for ii = 1, ninds - 1 do begin$
  results[ii].SED = fluxes[ii] / 10. * 29.44$
  results[ii].ESED = effs[ii] / 10. * 29.44$
  results[ii].FLAGS = flags[ii]$
  results[ii].RA = ra[ii]$
  results[ii].DEC = dec[ii]$
  results[ii].MCORR = mwcorr$
  results[ii].ZPCORR = zpcorr
endfor
RETURN, results

:: Get sources emitting Nlines lines at high confidence:

:: Trim and align databases
data = data[sinds]
phot = phot[minds]

B3 Get sources emitting Nlines lines at high confidence:

function getHighSnLines, mastercat, $ 
SNCUT = snout$

if NOT keyword_set(SNCUT) then snout = 5.
:: Set up the output storage
:: allowing for up to 10 high-s/n lines
output = {NUMLINES: 0, $
IDS: strarr(10),$
SNS: flirtarr(10)}$
output = replicate(output, n_elements(mastercat))$
:: Go through the lines and get their S/N
for ii = 0, n_elements(mastercat) - 1 do begin$
  lines = mastercat[ii].HASLINES$
  lines = strsplit(lines, ', /extr)
  if mastercat[ii].NUMLINES gt 0 then begin$
    tsn = flirtarr(mastercat[ii].NUMLINES)$
    for jj = 0, mastercat[ii].NUMLINES - 1 do begin$
      tl = lines[jj]$
      case tl of
        'Ha': tsn[jj] = mastercat[ii].SN_HA$
        'Hb': tsn[jj] = mastercat[ii].SN_HB$
        'OII': tsn[jj] = mastercat[ii].SN_OII$
        'OIII': tsn[jj] = mastercat[ii].SN_OIII$
        'SII': tsn[jj] = mastercat[ii].SN_SII$
        'MgII': tsn[jj] = mastercat[ii].SN_MgII$
        'LyA': tsn[jj] = mastercat[ii].SN_LyA
        ... ; More line names here.$
      endcase
    endfor
  endif
endif
RETURN, answer
end

:: Load spectral database
data.RA, data.DEC, 1.36000, $ 
minds, sinds, len
:: Count and store lines about S/N threshold
foo = where(tsn ge snout, nlines)
output[ii].NUMLINES = nlies
if nlies gt 0 then begin
  output[ii].IDS[0:nlies-1] = lines[foo]
  output[ii].SNS[0:nlies-1] = tsn[foo]
endif
endfor

RETURN, answer
end

:: Load photometry
phot = loadhdfphot(field)
:: Match with a 1" radius
spherematch, phot.RA, phot.DEC, $
APPENDIX C: COMPARISON TO EXTANT PHOTOMETRIC REDSHIFTS

Shipley et al. (2018) provide photometric redshifts for GLASS G800L sources in the HFF footprint. Fig. C1 compares these to the grism-only redshifts. Agreement is quite good for low risk sources, and unbiased for the full high-S/N + lines sample. The low risk sample is consistent with Gaussian errors, though errors may be slightly underestimated for the other samples (σ/√2⟨err⟩ > 1). Nevertheless, this analysis supports our conclusion that the ~2200 low risk objects should be immediately useful to analyses ‘straight out of the box.’

Figure C1. Similar to Fig. 4 but plotting HFF photometric redshifts from Shipley et al. (2018) (z_{phot}) against GLASS G800L redshifts (z_{spec}). Distributions are much wider, but agreement is still fair, with low risk sources having photo-z errors consistent with Gaussian noise. All samples show slight biases, but those for high-S/N + lines and low-risk sources are small in the mean.
APPENDIX D: FURTHER DATA EXAMPLES

Below are more examples of GLASS G800L spectra and combined spectrophotometry for select sources in the HFF footprint. All galaxies shown Fig. D1 have $S/N_{[O	ext{ III}]} \geq 5$ and are above the median brightness in the low risk sample. There are 304 such sources in the GLASS ACS data base. All galaxies in Fig. D2 are in the low risk sample with matching HFF photometry. There are 383 such objects in the GLASS ACS data base (3411 in total with HFF overlap).

Figure D1. Examples of the ∼300 bright, $S/N_{[O	ext{ III}]} \geq 5$ [O III] emitters in the glass data base.
Figure D1 —continued
Figure D1 — continued
Figure D1 – continued
Figure D2. GLASS G800L sources in the Abell 2744 and RXJ2248 parallel fields matched to HFF photometry from Shipley et al. (2018).
Figure D2 – continued
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