THE BRIGHTEST OF REIONIZING GALAXIES SURVEY: DESIGN AND PRELIMINARY RESULTS*

M. Trenti1, L. D. Bradley2, M. Stiavelli2, P. Oesch3, T. Treu4, R. J. Bouwens5,6, J. M. Shull7, J. W. MacKenty2, C. M. Carollo8, and G. D. Illingworth9

1 Center for Astrophysics and Space Astronomy, University of Colorado, 389-UCB, Boulder, CO 80309, USA; trenti@colorado.edu
2 Space Telescope Science Institute, 3700 San Martin Drive Baltimore, MD 21218, USA
3 Institute of Astronomy, ETH Zurich, CH-8093 Zurich, Switzerland
4 Department of Physics, University of California, Santa Barbara, CA 93106-9530, USA
5 Astronomy Department, University of California, Santa Cruz, CA 95064, USA
6 Leiden Observatory, University of Leiden, Postbus 9513, 2300 RA Leiden, The Netherlands
7 CASA, Department of Astrophysics and Planetary Science, University of Colorado, 389-UCB, Boulder, CO 80309, USA

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ABSTRACT

We present the first results on the search for very bright ($M_{AB} \approx -21$) galaxies at redshift $z \sim 8$ from the Brightest of Reionizing Galaxies (BoRG) survey. BoRG is a Hubble Space Telescope Wide Field Camera 3 (WFC3) pure-parallel survey that is obtaining images on random lines of sight at high Galactic latitudes in four filters (F606W, F098M, F125W, and F160W), with integration times optimized to identify galaxies at $z \gtrsim 7.5$ as F098M dropouts. We discuss here results from a search area of approximately 130 arcmin$^2$ over 23 BoRG fields, complemented by six other pure-parallel WFC3 fields with similar filters. This new search area is more than two times wider than previous WFC3 observations at $z \sim 8$. We identify four F098M-dropout candidates with high statistical confidence (detected at greater than 8$\sigma$ confidence in F125W). These sources are among the brightest candidates currently known at $z \sim 8$ and approximately 10 times brighter than the $z \approx 8.56$ galaxy UDFy-38135539. They thus represent ideal targets for spectroscopic follow-up observations and could potentially lead to a redshift record, as our color selection includes objects up to $z \sim 9$. However, the expected contamination rate of our sample is about 30% higher than typical searches for dropout galaxies in legacy fields, such as the GOODS and HUDF, where deeper data and additional optical filters are available to reject contaminants.

Key words: galaxies: evolution – galaxies: high-redshift

Online-only material: color figures

1. INTRODUCTION

The installation of Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST) opened new possibilities for discovery of $z > 7$ galaxies. Observations on the GOODS and HUDF fields have increased the sample of $z \gtrsim 7$ candidates to $N > 100$ (Oesch et al. 2010b; Bouwens et al. 2010a; McLure et al. 2010; Finkelstein et al. 2010; Wilkins et al. 2010). Legacy multi-wavelength coverage on these fields and the improved spatial resolution of WFC3 enabled preliminary characterization of the properties of these sources in terms of stellar mass, stellar populations, and size (Oesch et al. 2010a; Bouwens et al. 2010c; Labbé et al. 2010).

However, the current search area, while containing deep and ultradepth data, is modest (approximately 60 arcmin$^2$) and located within or around a single GOODS field. This provides significant uncertainty in the number density of $z \gtrsim 7$ galaxies owing to small-number statistics and cosmic variance (Bouwens et al. 2010a). This is especially severe at the bright end of the luminosity function (LF), where sources are most clustered and least abundant (e.g., see Trenti & Stiavelli 2008). These WFC3 observations suggest that the galaxy LF evolves sharply from $z \sim 6$ to $z \sim 8$, particularly at the bright end (Bouwens et al. 2010a). Such a trend is consistent with the underlying evolution of the dark matter halo mass function, which predicts well the LF evolution (Trenti et al. 2010), but stronger observational constraints on $M_*$ are needed.

Reducing uncertainty on the number density of bright $z \sim 8$ sources also benefits the determination of the LF faint-end slope $\alpha$. Fits to a Schechter (1976) LF, $\phi(L) = \phi_*(L/L_*)^\alpha \exp(-L/L_*)$, have a strong degeneracy between characteristic luminosity $M_\star = -2.5 \log_{10}(L_*)$ and $\alpha$ (Bouwens et al. 2007; Trenti & Stiavelli 2008). Measuring $\alpha$ is fundamental to assess whether galaxies emit enough photons to reionize the universe (Bunker et al. 2004; Chary 2008; Henry et al. 2009; Trenti et al. 2010; Robertson et al. 2010). Ground-based programs (Ouchi et al. 2009; Castellano et al. 2010) place useful constraints on $M_\star$ at slightly lower redshift ($z \lesssim 7$), but the impact of large-scale structure remains a concern, because all these searches are within legacy fields.

To complement the existing campaigns aimed at searching for $z \gtrsim 7.5$ galaxies, we introduce here the HST Brightest of Reionizing Galaxies (BoRG) survey. BoRG is based on pure-parallel observations with HST WFC3 while the telescope is pointing to a primary spectroscopic target (typically a foreground high-$z$ QSO). Because lines of sight are independent and well separated on the sky, cosmic variance is negligible. In contrast, cosmic variance introduces approximately 25% uncertainty, in addition to Poisson noise, in the number counts of $z \gtrsim 6$ galaxies for both the GOODS and the HUDF surveys. A survey with independent lines of sight provides an unbiased characterization of the LF bright end with errors equivalent to those of a continuous survey of about twice its area (Trenti & Stiavelli 2008).

The preliminary BoRG data set discussed here contains 29 lines of sight for a total of approximately 130 arcmin$^2$, more than
twice the area of the HUDF and GOODS-ERS observations in Bouwens et al. (2010a). This wide area allows us to identify galaxies that are good candidates for follow-up spectroscopic observations; all \( z \approx 8 \) galaxies in BoRG are significantly brighter than UDFy-38135539 for which Lehnert et al. (2010) reported detection of Ly\( \alpha \) emission at \( z \approx 8.56 \).

Section 2 of this Letter introduces the BoRG survey. Data reduction is discussed in Section 3. Section 4 presents our selection strategy along with estimates of contamination. Preliminary results are presented in Section 5 and compared with an independent analysis by Yan et al. (2010). Section 6 summarizes and concludes. We adopt a standard WMAP7 cosmology (Komatsu et al. 2011) and the AB magnitude scale (Oke 1974).

2. SURVEY DESIGN

The BoRG survey is designed to identify bright \( (m_{F125W} \lesssim 27) \) high-redshift galaxies from their broadband colors using the Ly\( \alpha \) break technique (Steidel et al. 1996). The primary aim of the survey is to select \( z \gtrsim 7.5 \) galaxies as F098M dropouts. Two near-IR filters (F125W and F160W) are used for source detection. One optical filter (F606W) is used to control the primary source of contamination from lower redshift \( z \approx 1.5 \) interlopers (see Section 4). As we detail below, the survey was designed to minimize the probability that artifacts and low-redshift interlopers may pass our selection criteria.

Parallel opportunities of program GO/PAR 11700 are at least three orbits in length (mostly 3–5 orbits). Each individual visit has a particular duration determined by the details of its primary program (see Table 1). The exposure time between filters has been allocated by keeping the relative depths approximately constant, within the constraints imposed by the primary program. In calculating the relative exposure times, we also took into account the effect of Galactic reddening. We used the primary line of sight as a proxy for the extinction expected in WFC3 images. From the reddening map of Schlegel et al. (1998) and extinction law of Cardelli et al. (1989), we derived the extinction in each band.

Dithering in pure-parallel observations is determined by the primary program, so it is usually absent because primary observations are spectroscopic. This introduces some challenges in the data analysis, especially with respect to systematic errors introduced by the detector, namely, hot pixels and detector persistence in the IR channel, which arises following observations of targets that saturate the detector (Dressel et al. 2010). The latter is of particular concern because of the possibility of introducing an artificial coherent signal into the detection band(s) for F098M dropouts, thereby leading to false candidates. To minimize the impact of persistence, we ensured that every observation of Program 11700 in either F125W or F160W is preceded in the same orbit by a comparably long F098M exposure. When possible, F160W observations follow F125W. As detector persistence decays over time (with approximately power-law behavior), any saturated target observed in a previous visit affects most the initial part of the pure-parallel orbit, which is the exposure in the dropout filter. With this strategy, persistence features are guaranteed not to contaminate the dropout selection. To ensure good sampling of the IR exposures, we opted for reading every 100 s (SPARS100). While the majority of cosmic rays are rejected by the calibration pipeline, owing to the multiple non-destructive readouts of WFC3, a small fraction may survive in the calibrated image. We thus split the total integration in each IR filter into at least two individual exposures. F606W exposures are split in \( N_s \geq 3 \) sequences (each 500–900 s) for cosmic-ray rejection, except for shallower fields, where \( N_s = 2 \) if the total F606W integration is less than 1000 s. Our design choices are aimed at maximizing the data quality, although a small price is paid in the term of signal-to-noise ratio \( (S/N) \). For example, our strategy to “shield” F125W and F160W observations from persistence by means of an F098M exposure carries some overhead because filter rotation happens during the observation window.

We also consider a small number of fields from another pure-parallel program with the same IR filters but with F600LP instead of F606W (GO/PAR 11702; PI: Yan). Images in program GO/PAR 11702 are not characterized by the optimization described above; for a given pointing, F098M exposures tend to be in different orbits than the redder IR filters. In addition, some IR filters only have a single exposure and both SPARS100 and SPARS200 sampling are used. Overall, this makes the additional data set potentially more vulnerable to spurious sources.

3. DATA REDUCTION AND CATALOG CONSTRUCTION

The images were reduced using standard techniques. For the WFC3/IR data, we recalibrated the raw data using calwfc3 using the most up-to-date reference files and our own custom flat fields generated by median stacking of publicly available WFC3/IR data in F098M, F125W, and F160W. We used SExtractor (Bertin & Arnouts 1996) to background subtract the FLT files prior to running multidrizzle (Koekemoer et al. 2002). The background levels were stored in the headers of each FLT file and are subsequently used by multidrizzle for cosmic-ray rejection. The individual exposures were aligned and drizzled on a common 0.08 arcsec pixel\(^{-1} \) scale using multidrizzle.

To identify F098M-dropout sources we first constructed a preliminary catalog with SExtractor, then we checked the source \( S/N \) reported by SExtractor and normalized the input rms maps if needed. Finally, we reran SExtractor to obtain the final source catalog. Below we describe these steps.

In each field, we identified sources from the F125W image using SExtractor in dual image mode. We required at least nine contiguous pixels with \( S/N > 0.7 \) for the preliminary catalog.

Multidrizzle introduces correlated noise in the images (Casertano et al. 2000). To derive realistic errors, one needs to rescale the rms map by measuring the noise in areas of size comparable to observed galaxies. Therefore, we selected 400 random pointings at distance \( d > 0.4 \) from detected sources. There we performed circular aperture photometry (radius \( r = 0.32 \)) with SExtractor in dual image mode. We used a synthetic detection image with artificial sources at the location of the random pointings and the actual images as photometry frames. We normalized the rms map of each filter requiring that, for these sky apertures, the median of the nominal error reported by SExtractor (FLUXERR\_APER) is equal to the rms of the measured flux (FLUX\_APER). This results in an average multiplication of the rms maps by 1.5 for F606W, by 1.15 for F098M, and by 1.1 for F125W and F160W.

After rescaling the rms maps, we reran SExtractor to create a final version of the catalogs. To include a source, we required detection with \( S/N > 8 \) in F125W and \( S/N > 3 \) in F160W for ISOMAG fluxes. Colors were computed from ISOMAG measurements. Total magnitudes were defined as AUTOMAG.

We derived median 5\( \sigma \) sensitivities in a circular aperture with radius \( r = 0.32 \) (median exposures times also listed) of \( m_{F606W} = 26.9 \) (\( \text{exp} = 2647 \) s), \( m_{F600LP} = 26.4 \) (\( \text{exp} = 2334 \) s), \( m_{F098M} = 26.8 \) (\( \text{exp} = 4515 \) s), \( m_{F125W} = 26.7 \) (\( \text{exp} = 2205 \) s), and \( m_{F160W} = 26.3 \) (\( \text{exp} = 1405 \) s). Table 1 reports the
individual field sensitivities. We used photometric zero points 26.08, 25.85, 25.68, 26.25, 25.96, respectively, for F606W, F600LP, F098M, F125W, F160W (Dressel et al. 2010).

4. SELECTION OF $z \approx 8$ GALAXY CANDIDATES

Candidate galaxies at $z \gtrsim 7.5$ are selected using broadband colors analogous to other $z \gtrsim 6$ galaxy surveys (Oesch et al. 2010b; Bouwens et al. 2010b). In short, we search for objects that have a strong break in the filter corresponding to the redshifted Ly$\alpha$ absorption at $z \gtrsim 7.5$. We use F098M as the dropout filter, requiring

$$m_{F098M} - m_{F125W} \geq 1.75.$$  (1)

If S/N < 1 in F098M, we replace the measured flux with its 1σ limit. Furthermore, to remove lower redshift red and/or obscured contaminants, we require that $m_{F125W} - m_{F160W}$ is moderately red at most:

$$m_{F125W} - m_{F160W} < 0.02 + 0.15 \times (m_{F098M} - m_{F125W} - 1.75).$$  (2)

The third condition we impose is a conservative non-detection at 1.5σ in the optical band available (F606W or F600LP).

These conditions have been chosen by optimizing the selection efficiency of genuine $z \gtrsim 7$ galaxies while minimizing contamination from low-redshift galaxies and cool stars. Our IR color–color selection window is shown in Figure 1, along with typical colors for possible galaxy contaminant sources. The figure is based on a library of 10 million galaxy spectral energy distributions (SEDs) constructed using different star formation histories, metallicities, and dust content (see Oesch et al. 2007). Figure 1 also shows the expected redshift distribution of Lyman break galaxies entering our selection window.

The availability of high-quality deep optical data appears to be the limiting factor in the rejection of low-redshift galaxy contaminants. In fact, passively evolving galaxies at $z \sim 1.5$ can contaminate the F098M-dropout selection when their 4000 Å Balmer break is misidentified as Ly$\alpha$ break if the data are not sufficiently deep to detect these sources in the optical bands (see also Henry et al. 2009; Capak et al. 2009). We estimate approximately 30% contamination using the GOODS-ERS data (Program 11359) which include F098M imaging. We estimate this number as follows: from the Bouwens et al. (2010a) data reduction we first identify F098M dropouts with $m_{F125W} \leq 27$ using the selection discussed above, but considering a version of the GOODS F606W image degraded to a 5" FWHM. We then check for contaminants by rejecting F098M dropouts with S/N > 2 in either B, V, or i (at their full depth). Approximately 30% contamination is in good agreement with the estimate based on the application of the color selection to our library of SED models (Figure 1).

Cool stars are another possible source of contamination. Our survey area is large and probes lines of sight at different Galactic

| Field  | R.A. (deg) | Decl. (deg) | F125W (m) | F160W (m) | F125W $t_\text{lim}$ (s) | F160W $t_\text{lim}$ (s) | F098M $t_\text{lim}$ (s) | F606W $t_\text{lim}$ (s) | F600LP $t_\text{lim}$ (s) |
|-------|-----------|------------|-----------|-----------|-------------------|-------------------|------------------|-------------------|-------------------|
| BoRG93 | 99.286    | -75.307    | 2412 26.6 | 2162 26.0 | 6218 26.8 | 4290 26.9 |
| BoRG81 | 88.277    | -64.091    | 2612 26.9 | 2012 26.3 | 6418 27.0 | 3624 27.1 |
| BoRG73 | 136.403   | 2.925      | 2709 27.1 | 1906 26.6 | 5518 27.0 | 3106 27.0 |
| BoRG70 | 157.712   | 38.059     | 1506 26.3 | 1306 26.1 | 3109 26.4 | 1815 26.4 |
| BoRG66 | 137.284   | -0.030     | 1806 26.8 | 1006 26.1 | 3909 26.9 | 2650 26.9 |
| BoRG58 | 219.230   | 50.719     | 2509 27.0 | 1806 26.6 | 4912 27.1 | 2754 26.8 |
| BoRG49 | 191.184   | 33.937     | 1506 26.6 | 1106 26.2 | 3409 26.8 | 1789 26.8 |
| BoRG45 | 141.390   | 40.005     | 1106 26.1 | 903 25.9  | 2806 26.2 | 1276 26.1 |
| BoRG39 | 138.567   | 28.363     | 2206 26.9 | 1706 26.5 | 4615 26.9 | 2571 26.9 |

Notes. Survey area: approximately 130 arcmin$^2$. Effective area for F098M-dropout detection: approximately 97 arcmin$^2$.

* Data missing due to scheduling constraint/conflict.
5. SAMPLE OF $z \sim 8$ CANDIDATES

Four objects satisfy our dropout selection, all from BoRG fields. Their photometry is reported in Table 2. Figures 2 and 3 show the candidates’ images. Here we discuss each candidate, critically assessing its likelihood to be at $z \gtrsim 7.5$, starting with the least robust. Three of these four objects have been identified as F098M dropouts by an independent analysis of our data (Yan et al. 2010). All fields with candidates contain at least two exposure frames per filter (taken in different orbits). We verified that candidates are detected in each individual F125W and F160W frame at $S/N$ consistent with scaling from the total to the individual exposure time.

5.1. BoRG66_1741-1157

This object is detected in F125W with $S/N = 8.7$, but only marginally in F160W ($S/N = 3.3$). Hence, it has the bluest $J−H$ color of the sample. With $Y − J = 1.9 \pm 0.6$, it lies at the edge of our dropout selection window, and its membership in the sample of $z \gtrsim 7.5$ candidates could be the result of photometric scatter. Its blue color could be due to contribution from strong Lyα emission in F125W. This object is not in the Yan et al. (2010) sample.

5.2. BoRG1k_0847-0733

This candidate also lies at the edge of the selection window and its inclusion in the sample could be due to photometric scatter in either $Y−H$ or $J−H$ color (with $\sim 60\%$ probability if errors are symmetric). There are hints of flux at optical wavelength: $(S/N)_{F606W} = 1.3$ ($S/N \gtrsim 1.3$ has probability $p \lesssim 6.6\%$ for Gaussian noise). The F606W exposure is shallow (Table 1): $t = 1260$ s (5σ mag limit 26.3). The dropout filter has a marginal detection ($S/N_{F098M} = 2.4$). Because of these multiple bits of circumstantial evidence, we consider the object a low-probability $z \gtrsim 7.5$ candidate, more likely to be a passive $z \sim 1.5$ galaxy.

5.3. BoRG0t_0958-0641

BoRG0t_0958-0641 is the faintest candidate in the sample, but has $(S/N)_{F125W} > 8$ and $(S/N)_{F160} = 6.8$ because of the significant exposure time in this field (Table 1). Data from programs 11700 and 11702 cover the region at slightly different orientations, providing some dithering. The candidate is well within the color–selection window for $z \gtrsim 7.5$ galaxies (Figure 1). Yan et al. (2010) do not consider this object a strong $z > 7.5$ candidate because they claim variability on the three-day timescale of the observations (see their Figure 4). We performed aperture photometry ($r = 0.32′′$) at the source location for the three epochs, and find no evidence of variability in F125W (measuring $m = 26.7, 26.8, 26.8$ with typical 1σ sky uncertainty of approximately 0.35 mag in each frame). We see evidence of variability in F160W at about 2σ confidence: $m = 26.2, 26.9, 27.2$ with 1σ error of approximately 0.35 mag. Closer examination highlights potential data quality issues. In the first epoch, the readouts of the F160W ramp for pixels within the source jump between readout eight and nine, indicating a cosmic ray hit. In the second epoch, there is a hot pixel located within this source. Because of the stable photometry in F125W, we consider intrinsic variability unlikely, although further observations would be useful to clarify the nature of this source.
The Astrophysical Journal Letters, 727:L39 (6pp), 2011 February 1

Trenti et al.

Figure 2. Region (3′2 × 3′2) surrounding the most robust BoRG F098M-dropout candidates (left to right: F606W, F098M, F125W, F160W).
(A color version of this figure is available in the online journal.)

Figure 3. Same as Figure 2, but showing the least robust BoRG dropouts.
(A color version of this figure is available in the online journal.)

Table 2

| Dropout             | mJ             | IR Colors | S/N       | Stellarity |
|---------------------|----------------|-----------|-----------|------------|
| BoRG66_1741-1157    | 137.2732       | 26.2 ± 0.2| 1.9 ± 0.6 | −0.8       |
| BoRG1k_0847-0733b   | 247.8968       | 25.5 ± 0.1| 1.9 ± 0.4 | 1.3        |
| BoRG0t_0958-0641b,c | 117.7142       | 26.7 ± 0.2| > 2.6     | −0.9       |
| BoRG58_1787-1420b   | 219.2107       | 25.8 ± 0.1| > 2.8     | 13.2       |

Notes. Photometric properties of candidates and their coordinates (Deg, J2000 system). Magnitude mJ is AUTOMAG from SExtractor. Colors are derived from ISOMAG (fluxes below 1σ have been replaced with 1σ limit). SExtractor Stellarity parameter also reported.

5.4. BoRG58_1787-1420

This is the most robust candidate of the sample, with all its properties fully consistent with being a z ≳ 7.5 galaxy. The measured colors are well within the selection window, even after taking into account 1σ errors. The object lies on the z ≳ 7.5 galaxy tracks. There is no flux at optical wavelength (S/N)F606W < 0).

6. DISCUSSION AND CONCLUSIONS

In this Letter, we discuss the preliminary results from the BoRG survey on the search of bright z ≳ 7.5 galaxies identified as F098M dropouts using HST WFC3 data. By analyzing 29 independent lines of sight, we identify four dropouts with (S/N)F125W > 8σ. Two objects lie near the selection window border, and they are possibly low-redshift interlopers scattered into the selection (but it is similarly likely that photometric scatter removes objects from the sample). The remaining candidates satisfy all the expected properties for z ≳ 7.5 objects with high confidence.

Detailed discussion on the implications for the evolution of the galaxy LF is deferred to a future paper (L. D. Bradley et al. 2011, in preparation). There we will also attempt to extend the detection of dropouts to fainter limits and carry out artificial source recovery simulations to estimate the effective volume of the BoRG survey as a function of magnitude. Here, we consider a magnitude limit mF125W ≤ 26.2 (equivalent to M ≤ −20.9), where completeness is close to unity in all regions of the BoRG data not occupied by a foreground object. To estimate our effective area, we masked all pixels at distance d ≤ 0′′.4 from a pixel belonging to the SExtractor segmentation map and counted the remaining pixels, deriving an effective search area of approximately 97 arcmin². Further assuming a pencil-beam
geometry with $7.5 \leq z \leq 8.5$, we derive a comoving volume of $2.3 \times 10^5 \text{ Mpc}^3$. From the best-fit $z = 8$ LF derived by Bouwens et al. (2010a) based on ERS and HUDF data, we expect $N \sim 2.5$ galaxies with $M \leq -20.9$ in our search area. Three candidates at $m_{F125W} \leq 26.2$ are fully consistent with this expectation, even after taking into account a contamination rate of approximately 30% from low-$z$ galaxies (Section 4), but alternative models cannot be strongly ruled out. For constant $\alpha = -2.0$ and $\phi_* = 0.38 \times 10^{-3} \text{ Mpc}^{-3}$ (Bouwens et al. 2010a), we derive $M_* = -20.2 \pm 0.3 (68\% \text{ confidence}).$ Quadrupling the BoRG area would allow us to set $\Delta M_* < 0.3$ at 99% confidence. Similar future pure-parallel observations (e.g., GO/PAR 12286 PI Yan) will contribute toward this goal by approximately doubling the current search area.

Finally, BoRG58_1787-1420 represents an ideal candidate for follow-up spectroscopic investigations. This galaxy is about 10 times brighter than UDFy-38135539 for which Lehnert et al. (2010) claimed detection of Ly$\alpha$ emission at $z = 8.56$. BoRG58_1787-1420 could potentially yield a more secure line identification if the equivalent width is similar to the $\sim 1900 \text{ Å}$ of UDFy-38135539 or alternatively a comparable line flux (approximately $6 \times 10^{-18} \text{ erg s}^{-1} \text{ cm}^{-2}$) for a 200 Å equivalent width. In addition, from Trenti et al. (2010), we derive $M_h \sim 7 \times 10^{11} M_\odot$ as the host-halo mass for BoRG58_1787-1420. This galaxy likely lives in an overdense region of the universe, where the intergalactic medium is ionized at early times, facilitating escape (and detection) of the Ly$\alpha$ radiation.

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