SOUTHERN COSMOLOGY SURVEY. III. QSOs FROM COMBINED GALEX AND OPTICAL PHOTOMETRY

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ABSTRACT

We present catalogs of QSO candidates selected using photometry from Galaxy Evolution Explorer (GALEX) combined with the Sloan Digital Sky Survey (SDSS) in the Stripe 82 region and Blanco Cosmology Survey (BCS) near declination −55°. The SDSS region contains $\simeq 700$ objects with magnitude $i < 20$ and $\simeq 3600$ objects with $i < 21.5$ in a $\simeq 60$ deg$^2$ sky region, while the BCS region contains $\simeq 280$ objects with magnitude $i < 20$ and $\sim 2000$ objects with $i < 21.5$ for a 11 deg$^2$ sky region that is being observed by three current microwave Sunyaev–Zeldovich surveys. Our QSO catalog is the first one in the BCS region. Deep GALEX exposures ($\simeq 2000$ s in $F_{\text{UV}}$ and $N_{\text{UV}}$, except in three fields) provide high signal-to-noise photometry in the GALEX bands ($F_{\text{UV}}, N_{\text{UV}} < 24.5$ mag). From this data, we select QSO candidates using only GALEX and optical $r$-band photometry, using the method given by Atlee & Gould. In the Stripe 82 field, $60\%$ ($30\%$) of the GALEX-selected QSOs with optical magnitude $i < 20$ ($i < 21.5$) also appear in the Richards et al. QSO catalog constructed using five-band optical SDSS photometry. Comparison with the same catalog by Richards et al. shows the completeness of the sample is approximately $40\%$ ($25\%$). However, for regions of the sky with very low dust extinction, like the BCS 23-hr field and the Stripe 82 between $0^\circ$ and $10^\circ$ in RA, our completeness is close to $95\%$, demonstrating that deep GALEX observations are as efficient as multiwavelength observations at finding QSOs. GALEX observations thus provide a viable alternate route to QSO catalogs in sky regions where $u$-band optical photometry is not available. The full catalog is available at http://www.ice.csic.es/personal/jimenez/PHOTOZ.

Key words: atomic processes – cosmology: theory – early universe – intergalactic medium

1. INTRODUCTION

With ground-based telescopes surveying the sky at millimeter wavelengths and angular resolutions of around 1 arcmin (APEX,6 SPT,7 ACT8), and the launch of the Planck satellite, we will be soon exploring how structures grew in the universe using the Sunyaev–Zeldovich (SZ) effect (Sunyaev & Zeldovich 1972). Indeed, the SPT Collaboration has recently released its first results of their blind survey (Staniszewski et al. 2008). How-
sample is complete at the 40% and 25% levels in the brighter and fainter samples, respectively, when compared with the QSOs in the Richards et al. (2008) catalog. Our completeness is significantly higher ~95% for regions of the sky with very low dust extinction. We provide an electronic version of the QSO catalogs at http://www.ice.csic.es/personal/jimenez/PHOTOZ.

2. INPUT CATALOGS

Our GALEX observations comprise a Legacy program awarded in Cycle 3, with the goal of mapping 100 deg$^2$ with 3 ks exposure time per pointing in both the $F_{UV}$ and $N_{UV}$ filters. We chose to map roughly 11 deg$^2$ covering the BCS\footnote{http://cosmology.uiuc.edu/BCS.} 23-hr field at declination $-55^\circ$, and a larger area of the equatorial Stripe 82 field covered by SDSS. Both areas have griz optical observations, and SDSS also has $u$ observations. We took advantage of the fact that the Stripe 82 survey area includes a number of the GALEX Medium Imaging Survey fields, which already had many observations of 1.5 ks or longer, and therefore needed only partial additional observations to reach our 3 ks target. When our program is finished, we will have collected around 210 ks of new GALEX observations.

Matches between the GALEX detections and SDSS or BCS data were done by initially assigning optical sources to a particular GALEX pointing if they fall within 35.1 of the GALEX field center. This cuts the noisiest region of the GALEX fields (near the edges), while maintaining complete sky coverage between neighboring fields (i.e., leaving no gaps). Within every GALEX field, each optical source is assigned a match to the nearest GALEX object detected in the $N_{UV}$ band, if the GALEX object is within a 4'' radius of the optical source; this is a relatively conservative matching radius (Agüeros et al. 2005). After all sources in the field are assigned, the combined catalog is searched to test whether any two optical sources are assigned to the same GALEX object. In the case of overlapping assignments, the closest optical source to the GALEX position is selected and the other is removed from the catalog. Optical sources which do not have a GALEX detection are removed from the catalog. This fraction is less than 1% of the total entries.

Because of the differences in the point-spread functions of different instruments and between bands, simple aperture

\footnote{www.physics.drexel.edu/~gtr/outgoing/nbckde/tab1.dat.bz2.}
Table 1
Color Criteria from Atlee & Gould (2007) Used in This Study

| Boundary Criterion |
|--------------------|
| FUV–NUV $\geq 37.314$ (NUV–R) $- 70.70372$ |
| FUV–NUV $\geq (NUV–R) - 0.5$ |
| NUV–R $\geq -0.895$ |
| FUV–NUV $\geq 0.5$ |
| FUV–NUV $\leq 4.343$ |

Table 2
Completeness of Our QSO Sample in the SDSS Stripe 82 When Compared with the Richards et al. (2008) Catalog

|                      | $i < 20$ | $i < 21.5$ |
|----------------------|----------|------------|
| SDSS Stripe 82 (%)   | 40       | 25         |
| SDSS Stripe 82 (0–10 R.A.) (%) | 95 | 95 |

Notes. SDSS Stripe 82 (0–10 R.A.) corresponds to the lowest extinction region and the QSO detection efficiency increases. See the text for more details.

For the BCS, we use the catalog developed by Menanteau et al. (2008). In this case the optical magnitudes are obtained using the magauto feature in SExtractor, providing a good estimate of the total photometry for each BCS band. Note that $r$-band magnitudes in BCS differ only by $\sim 0.03$ mag from the SDSS $r$ band, which makes no difference in the QSO photometric selection.

quality of the fit and combined to obtain the best-fitting profile. This measurement provides our estimate of the total photometry for each SDSS band.

For the BCS, we use the catalog developed by Menanteau et al. (2008). In this case the optical magnitudes are obtained using the magauto feature in SExtractor, providing a good estimate of the total photometry for each BCS band. Note that $r$-band magnitudes in BCS differ only by $\sim 0.03$ mag from the SDSS $r$ band, which makes no difference in the QSO photometric selection.

12 www.sdss.org/dr5/algorithms/photometry.html.
13 http://terapix.iap.fr.
3. CATALOG CONSTRUCTION AND DESCRIPTION

We construct our catalog of QSO candidates by using the selection criteria of Atlee & Gould (2007) described in their Table 1 and Section 3, which we repeat here in our Table 1.

Figure 1 shows the QSO candidates in the $F_{\nu 2}^{-N_{\nu 2}}$ versus $N_{\nu 2}$ color–color plot for the Stripe 82 region. After all selection cuts have been applied, we are left with a catalog of \( \approx 1000 \) objects for a magnitude cut of \( i < 20 \). Because we have SDSS photometry for all candidates, we can compare with the catalog from Richards et al. (2008). We match the two catalogs by finding matches within a 1\(^\circ\) radius of each object in the Richards et al. catalog. We find that every object from our catalog matches to only one Richards et al. object. As a function of magnitude we find that for \( i \approx 19.1 \) about 70% of our QSO candidates are in the Richards et al. catalog. This ratio decreases

### Table 3

| $g$   | $r$   | $i$   | $z$   | NUV | FUV | ML $z$ | R.A. (deg) | DEC (deg) | Obj. | Dup. |
|-------|-------|-------|-------|-----|-----|--------|------------|-----------|------|------|
| 21.35 | 20.92 | 20.67 | 20.43 | 20.91 | 22.41 | 0.390  | 348.68307 | −54.17750 | 1    | 2    |
| 20.91 | 20.36 | 20.09 | 19.96 | 20.84 | 21.77 | 0.400  | 349.20099 | −54.34292 | 1    | 2    |
| 21.00 | 20.67 | 20.20 | 19.77 | 21.76 | 22.87 | 0.820  | 348.65649 | −54.29034 | 1    | 1    |
| 21.68 | 21.06 | 20.69 | 20.39 | 22.00 | 23.42 | 0.670  | 349.01151 | −54.55352 | 1    | 1    |
| 22.18 | 21.56 | 20.88 | 21.14 | 22.70 | 24.30 | 0.620  | 349.12097 | −54.39764 | 1    | 1    |
| 21.67 | 21.42 | 21.20 | 20.37 | 22.23 | 23.08 | 0.730  | 348.18915 | −54.36168 | 1    | 2    |
| 22.19 | 21.35 | 21.05 | 21.04 | 22.16 | 23.20 | 0.530  | 348.48636 | −54.36288 | 1    | 1    |
| 22.14 | 21.40 | 21.09 | 20.73 | 22.59 | 24.02 | 0.680  | 348.43222 | −54.50095 | 1    | 1    |
| 21.29 | 20.35 | 20.01 | 19.70 | 21.89 | 23.30 | 0.410  | 348.67194 | −54.21693 | 1    | 1    |
| 22.58 | 22.01 | 21.45 | 20.66 | 22.98 | 24.24 | 1.020  | 349.01196 | −54.36000 | 1    | 2    |
| 21.81 | 21.26 | 20.82 | 20.47 | 22.54 | 23.90 | 0.690  | 349.13736 | −54.36909 | 1    | 1    |
| 19.37 | 19.16 | 19.12 | 19.14 | 20.15 | 22.02 | 0.650  | 348.44855 | −54.45570 | 1    | 1    |
| 22.36 | 22.02 | 21.41 | 20.99 | 22.55 | 23.27 | 0.840  | 348.42685 | −54.24467 | 1    | 1    |
| 20.83 | 20.52 | 20.52 | 20.35 | 21.02 | 21.68 | 0.250  | 348.55483 | −54.24429 | 1    | 1    |
| 21.92 | 21.24 | 20.95 | 20.90 | 21.98 | 23.63 | 0.640  | 348.64935 | −54.44136 | 1    | 1    |
| 21.66 | 21.26 | 21.26 | 20.94 | 21.95 | 23.72 | 0.840  | 348.25293 | −54.46777 | 1    | 2    |
| 23.33 | 21.38 | 20.90 | 21.44 | 22.36 | 23.89 | 0.600  | 348.74884 | −54.33202 | 1    | 2    |
| 21.20 | 20.95 | 20.43 | 20.00 | 21.61 | 23.49 | 0.830  | 348.46118 | −54.36068 | 1    | 1    |
| 22.34 | 21.62 | 18.65 | 22.28 | 22.79 | 0.680  | 348.12775 | −54.48014 | 1    | 1    |
| 22.01 | 21.52 | 21.32 | 21.39 | 22.88 | 24.14 | 0.640  | 348.47693 | −54.43538 | 1    | 1    |

**Notes.** The BCS magnitudes have been computed using the magauto option in Sextractor. GALEX magnitudes were computed using the magauto option in Sextractor. ML $z$ refers to the best maximum likelihood photo-z estimate as described in Niemack et al. (2009). Obj. column is number of GALEX objects within search radius. Dup. column is Optical galaxies matched to GALEX objects. The catalog is available at http://www.ice.csic.es/personal/jimenez/PHOTOZ.
to 60% for \( i < 20 \) and 30% for \( i < 21.5 \). Using these numbers we conclude that the catalogs are complete with respect to the Richards et al. sample at the 40% level up to \( i < 20 \) and 25% for \( i < 21.5 \). Because the \textit{GALEX} observations are significantly influenced by diffuse dust extinction, we explore the completeness for regions in Stripe 82 with the lowest dust extinction. The lowest extinction region is in the range \( 0 < \text{R.A.} < 10 \). In this region we find 95% matches for \( i < 21.5 \) and a similar completeness level when compared with the Richards et al. catalog. This demonstrates that our technique is as successful as optical multiwavelength searches in low extinction regions of the sky.

To illustrate graphically the success of our scheme, we compare with the most likely color–color selection by Richards et al. (2004) (see Table 2), which has proven very successful at photometrically finding QSOs. This is shown in Figure 2. The locus that Richards et al. (2004) use to select QSO candidates is enclosed by the solid lines. Objects that fall within this region are more than 95% likely to be true spectroscopically confirmed QSOs (Richards et al. 2004). For a magnitude cut of \( i < 20 \) (21.5) we find that only 20% (40%) of our objects lie outside the Richards-defined QSO region. Because we can compute accurate photometric redshifts using the \textit{GALEX} and optical bands as done in Niemack et al. (2009), we can test how many of our candidates are at \( z = 0 \) and are therefore likely stars. We show the redshift distribution and spatial distribution of the QSO candidates in Figures 3 and 5, for the Stripe 82 and BCS 23-hr regions, respectively. Between 13% and 20% of the QSO candidates are likely stars; they all lie outside the Richards region.

Our success rate at detecting QSOs is higher than Atlee & Gould (2007) because we have deeper \textit{GALEX} exposures (\( \gtrsim 2000 \) s, except in three fields, which is 20 times longer than the \textit{GALEX} all sky survey they used), which allow for better sampling of the QSO emission features in the otherwise power lawlike UV spectrum of the QSOs. In particular, we find that at the bright end (\( i < 19.1 \)) our technique finds 100% of the QSOs of Richards et al. catalog. For dimmer samples the success rate is lower, as more and more QSOs are not detected in the \textit{GALEX} bands, especially in the \( F_{UV} \). We interpret this as an effect of extinction: the Richards et al. QSO missing from the \textit{GALEX} selection are redder in the UV.

For the BCS sample we do not have \( u \)-band optical data, so we directly apply the cuts from Table 1 and present the redshift distribution and location of these host in Figures 4 and 5. As expected and discussed by Richards et al. (2004), we are selecting QSOs at \( z < 2 \). This can be seen in both Figures 3 and 4. The BCS catalogs contain \( \approx 280 \) objects with magnitude \( i < 20 \) and \( \approx 2000 \) objects with \( i < 21.5 \) for a 11 deg\(^2\) region. The BCS 23-hr region is one of the lowest extinction areas in the sky, which allows for deeper \textit{GALEX} observations than in the Stripe 82 and a higher rate (50%–100%) at finding QSO candidates. In fact, for the BCS 23-hr region we find \( \approx 100 \) QSOs deg\(^{-2}\) which is similar to the QSO density found by Richards et al.

Tables 3 and 4 show a sample of the catalog available online (www.ice.csic.es/personal/jimenez/PHOTOZ) and describe the different entries for the catalog. We give the maximum likelihood redshift using the method described in Niemack et al. (2009) and the corresponding optical magnitudes in each survey. On the web page we provide catalogs for the two different magnitude cuts (\( i < 20 \) and \( i < 21.5 \)). These catalogs will be updated online as our \textit{GALEX} observations are completed.

4. CONCLUSIONS

We have constructed a new catalog of photometric QSO candidates from \textit{GALEX} photometry and optical \( r \)-band data. In the SDSS Stripe 82 field, our selection criteria are successful in finding true QSOs at the 60% (30%) level with \( i < 20 \) (\( i < 21.5 \)) when compared with the Richards et al. (2008) QSO catalog constructed using 5-band optical SDSS photometry. Comparison with the same catalog by Richards et al. shows that the completeness of the sample is 40% (25%). For low extinction regions our completeness grows to 95%. This catalog covers some of the areas currently being scanned by microwave SZ experiments. It therefore provides a point-source catalog to be masked out in these experiments. It can also be used to cross-correlate QSO positions with microwave temperature fluctuations to detect the SZ distortions due to the energy ejection from QSOs into the surrounding intergalactic medium (Chatterjee & Kosowsky 2007; Chatterjee et al. 2008; Scannapieco et al. 2008). Even at medium depth, \textit{GALEX} coverage will have substantial utility in combination with optical imaging programs like Pan-STARRS (which does not have \( u \)-band coverage). We anticipate that a \textit{GALEX} observation program covering the SZ survey areas at medium depth in combination with single \( r \)-band photometry will be extremely useful to the SZ community. New QSO catalogs will also enable further studies including absolute astrometric reference frames.

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