Moderately and Extremely Red Galaxies in the Fields of Radio-Loud Quasars at $z = 1 - 2$

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**Abstract.** We present new studies of an excess population of mainly red galaxies around a sample of 31 radio-loud quasars at $z = 1 - 2$. These fields have a surface density of extremely red objects (EROs) at least a factor of 2.4 greater than the general field. Assuming the EROs are passively evolved early-type galaxies at the quasar redshifts, we find that they typically have $L \sim L^*$. $H$-band adaptive optics imaging of one field is used to estimate "structural redshifts" for two moderately red bulge-dominated galaxies using the Kormendy relation. Finally, quantitative photometric redshifts and SED fits are discussed for selected galaxies.

1. Introduction

It is of considerable interest to efficiently identify structures of galaxies at $z > 1$ in order to study the evolution of both galaxies and galaxy clustering. Radio-loud quasars (RLQs) are obvious signposts around which to search for clusters at $z>1$. In Hall & Green (1998) we presented optical and near-IR imaging of a sample of 31 RLQs at $z=1-2$ which revealed an excess population of predominantly red galaxies consistent with being at the quasar redshifts. Direct spectroscopic confirmation of overdensities at the quasar redshifts is still lacking, but various new observations of these fields and further analyses of the existing data strengthen many of our previous conclusions (Hall et al. 2000).

2. Surface Density of Extremely Red Objects

Since the appearance of infrared array detectors, numerous discoveries of Extremely Red Objects (EROs) have been noted in the literature (see Thompson et al. (1999a) for an overview). Various observations have hinted that EROs are more common along lines of sight to distant AGN (see Smail et al. (1999) for a recent summary). We have used our $z = 1 - 2$ RLQ fields to test this hypothesis.
more carefully. With a conservative stellar contamination correction, we find a surface density of $0.117^{+0.035}_{-0.027}$ arcmin$^{-2}$ for $K' \leq 19$ EROs with $R - K' \geq 6$, 2.4 times higher than the field counts of Thompson et al. (1999b). With a minimal correction, we find a factor of 4 excess. As for $J-K$ selected EROs, Drory et al. (1999) find a surface density of $0.098 \pm 0.009$ arcmin$^{-2}$ for $K \leq 19.5$ EROs with $J-K \geq 2.5$ ("$J$-band dropouts"). In three fields from Hall, Green & Cohen (1998) with deep $J$ data, we find one such ERO $(0.041^{+0.05}_{-0.023}$ arcmin$^{-2}$), but in the Q 1126+101 field we find five such EROs $(0.58^{+0.35}_{-0.23}$ arcmin$^{-2}$).

The presence of the quasars in these fields allows us to estimate the luminosities of the $r-K$ selected EROs by assuming they are at the quasar redshifts. Applying elliptical $k$- and $e$-corrections from Fioc & Rocca-Volmerange (1997), we find $M_K^{ERO} = -24.1 \pm 0.4$, completely consistent with the Gardner et al. (1997) measurement of the Schechter function $M_K = -24.2 \pm 0.2$ at $<z> = 0.14$ ($q_0=0.1$, $H_0=75$, and our aperture sizes; see HG98 §5.1). Thus these EROs are consistent with being drawn from the bright end of the luminosity function of early-type galaxies. The higher density of such EROs in RLQ fields can then be easily understood if the RLQs are preferentially located in galaxy overdensities. Of course, if the EROs are dusty starburst galaxies they will have higher luminosities, $L>L^*$. However, if dust reddening is significant in them, $R-K$ selected EROs should be $J-K$ EROs as well, which is rarely the case. The $J-K$ selected EROs may be dusty galaxies which at these bright magnitudes are rare in dense environments as well as the field, as suggested by at least one object in the exceptional Q 1126+101 field discussed in §4 below.

3. $H$-band Adaptive Optics Imaging of Moderately Red Galaxies

Little information is available on the detailed morphologies of EROs. Ground-based IR adaptive optics imaging is an obvious way to obtain such information. There is a $V=10.3$ star only 90" from Q 0835+580, a $z = 1.54$ RLQ surrounded by an obvious overdensity of red galaxies, so we targeted this field with the CFHT Adaptive Optics Bonnette. Unfortunately, with the IR imaging then available we were unable to select any ERO targets near the guide star, so we instead observed two moderately red galaxies in this field in the $H$ band with the intention of studying galaxies at the quasar redshift as follows. The data show that both galaxies are much better fit with $r^{1/4}$-law profiles than exponential disk profiles; thus, we can use the Kormendy relation between effective radius and average effective surface brightness to determine what redshifts are consistent with the objects' observed sizes and surface brightnesses (Eisenhardt et al. 1996).

To perform this analysis we use the elliptical colors and evolutionary and $k$-corrections of Poggianti (1997) to correct from observed $H$ to rest $B$. For a range of assumed redshifts, we compute the rest-frame $B$-band surface brightness within $r_e$ and the physical size $R_e$ corresponding to the observed $r_e$. In Fig. 1 we show the tracks as a function of redshift for both objects (with various redshifts marked with ticks and labelled), along with data for local ellipticals from Sandage & Perelmuter (1990). The tracks for both objects we observed intersect the surface brightness-effective radius relation for ellipticals both at low and high redshift, $z \sim 0.03 - 0.17$ or $z \sim 1 - 1.35$. We compare these redshift estimates with those from photometric redshifts in the next section.
4. Photometric Redshifts and Spectral Types

To compute photometric redshifts for selected objects, the spectrum of a solar metallicity GISSEL model with synthetic Kurucz spectra (Bruzual & Charlot 1996) was calculated for ages 0–20 Gyr and redshifts $z=0–4$ assuming either an instantaneous burst or a constant SFR, and with dust added following Calzetti (1997) for $E(B-V)=0, 0.1, 0.2, 0.4 ... 1.6$ (ten values in all). Fluxes were computed and compared to observations in available filters to construct $\chi^2$ contour plots in age-$z$ space for each value of $E(B-V)$ in each SFR scenario (Fig. 2).

Considering the two moderately red galaxies with AO imaging, we find that Q 0835+580 (112) is not well fit by any of our simple models ($\chi^2_{\nu} \geq 5$). A composite stellar population may improve the fit, but that may cast some doubt on its identification as an elliptical galaxy. Q 0835+580 (106) fares somewhat better; it is well fit ($\chi^2_{\nu} \approx 1$) by a $\geq 1$ Gyr old instantaneous burst with $E(B-V)=0.2$ at $z=0.7$ (Fig. 2). This is lower than the structural redshift estimate of §3, which may indicate a problem with one of the redshift estimates. On the other hand, if we correct the central surface brightness to account for the 1.15 mag of extinction implied by the SED fit, then the structural redshift becomes consistent with the $z=0.7$ photometric redshift. This concordance suggests that Q 0835+580 (106) may be a dusty, bulge-dominated galaxy at $z=0.7$, although this conclusion may depend on the details of the appropriate evolutionary- and $k$-corrections as well as the evolution of dust extinction after episodes of star formation. The safest course may be to obtain spectroscopy and higher resolution imaging to under-
stand these galaxies more fully and to calibrate the photometric and structural redshift techniques in order to utilize their full potential.

Another class of galaxies for which photometric redshifts and SEDs may prove useful are the “J-dropouts” (§2), since they may be dusty or at $z \geq 2.5$ or both. A preliminary analysis of the brightest J-dropout in this field, Q 1126+101 (425), is presented in Hall et al. (1999). It is found to have $E(B-V) \sim 0.5$ and $z_{ph}=3.5\pm0.5$, and is background to the $z=1.54$ quasar at >99.9% confidence for all $E(B-V)<0.7$. For a constant SFR, the object’s very red colors require $E(B-V)>0.5$ at any $z$ to remain younger than the universe in any reasonable cosmology. The required dust is consistent with its observed $J-K$ color being redder than that of HR10, the prototypical dusty ERO. Since none of our other RLQ fields with $J$ data show an excess of J dropouts, they are probably background objects unrelated to the quasars. The 4000 Å break at $z=3.5\pm0.5$ can then explain their red $J-K$ colors, although some of them such as Q 1126+101 (425) may still be very dusty. Further details can be found in Hall et al. (2000).

5. Discussion and Conclusions

The fields of 31 $z = 1 - 2$ RLQs found by Hall & Green (1998) to have an excess population of predominantly red galaxies also have a surface density of $R - K$ selected EROs a factor of 2.4 to 4 times higher than that of the field. This means 60-80% of these EROs are likely to be at the quasar redshifts, enabling us to estimate their absolute magnitudes more accurately than previous studies. Applying $k$-corrections and minimal $e-$corrections for passively evolving ellipticals formed at high $z$, we find that the EROs have $M_K \approx M_K^*$ with a dispersion of $\pm0^m.4$. Thus they are consistent with being drawn from the bright end of the
early-type galaxy LF. The higher density of such EROs in RLQ fields can be
easily understood if the RLQs are preferentially located in galaxy overdensities.
In contrast, J − K selected EROs seem to be rare in RLQ fields as well as the
general field. The photometric redshift of one such “J-dropout” shows that it is
dusty and background to the quasar, suggesting that the excess of J − K selected
EROs in one of our RLQ fields is due to a serendipitous background structure.

Using high-resolution imaging from adaptive optics or HST it should be
possible to derive structural redshifts for bulge-dominated galaxies in these fields
using the Kormendy relation. We have attempted this with two moderately red
galaxies in the Q 0835+580 field; both are consistent with ellipticals at z ≤ 0.2 or
z = 1−1.35. We attempted to confirm this using photometric redshifts. One object
is not well fit by simple stellar population models. The other is very well fit as a
slightly dusty galaxy, but at z ∼ 0.7, not z = 1−1.35 as predicted. The estimated
dust reddening may explain why the structural redshift estimate was off, but a
better understanding of the object’s stellar populations is needed to be sure. It
seems likely that spectroscopy will be required to calibrate the photometric and
structural redshift techniques before they realize their full potential.

We have recently obtained ∼8′ diameter J and K_s images of the Q 0835+580
field (Hall et al. 2000). These are being used to select spectroscopic followup
targets and AO targets to study the accuracy of “structural redshifts” from the
Kormendy relation, and will be combined with upcoming wide-field BVRIZ
imaging to improve our photometric redshifts and extend them to more galaxies.

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