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In order to further the study of these galaxies, we have taken near-infrared spectra with the Keck Telescope of three EROs found in the fields of high redshift AGN. The continuum is well detected in each, but no emission lines or spectral breaks are detected. We have found probable redshifts, extinctions, ages, and star formation histories for each of these EROs based on fitting their spectral energy distributions. For every age and star formation model, the fits are constrained to small regions in redshift and reddening. Due to the unknown nature of these objects, we cannot rule out values of $A_v$ as high as 15 at low redshifts. None of the EROs have spectra consistent with the redshifts of their nearby high-redshift objects.

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Infrared Observations of Three Extremely Red Objects

T.M. Glassman and J.E. Larkin

Dept. of Physics and Astronomy, University of California, Los Angeles

ABSTRACT

Deep infrared and optical surveys have recently revealed a large number of very red 
\((R - K > 6)\) galaxies, labeled Extremely Red Objects (EROs). Many have been identified with broadband photometry, but very few have been observed spectroscopically. From the limited spectra available, it appears that they may form a heterogeneous population. There are EROs at high redshifts with dusty, active star formation (Dey et al. 1999) as well as EROs with old stellar populations and little dust (Soifer et al. 1999).

In order to further the study of these galaxies, we have taken near-infrared spectra with the Keck Telescope of three EROs found in the fields of high redshift AGN. The continuum is well detected in each, but no emission lines or spectral breaks are detected. We have found probable redshifts, extinctions, ages, and star formation histories for each of these EROs based on fitting their spectral energy distributions. For every age and star formation model, the fits are constrained to small regions in redshift and reddening. Due to the unknown nature of these objects, we cannot rule out values of \(A_v\) as high as 15 at low redshifts. None of the EROs have spectra consistent with the redshifts of their nearby high-redshift objects.

Subject headings: galaxies: formation - galaxies: stellar content - infrared: galaxies

1. INTRODUCTION

In recent years a new class of galaxies, called "Extremely Red Objects" (EROs), has been detected in deep infrared surveys. They are usually defined as resolved objects with \((R - K) \geq 6\) mag. They have a large surface density on the sky although there is no agreement on the exact number, in part due to slightly different definitions. Thompson et al. (1999) measured a surface density of \(0.039 \pm 0.016\) arcmin\(^{-2}\) in the field with \(K' \leq 19.0\) and \((R - K') \geq 6\) and Soifer et al. (1999) quote \(0.01\) arcmin\(^{-2}\) in the field with \(K < 18\) and \((R - K) > 6\). Dey et al. (1999) quote a density in the field of \(0.1\) arcmin\(^{-2}\) for \((R-K') \geq 6\) and \(K' \leq 17.5\) and \(0.7\) arcmin\(^{-2}\) for \((R-K') \geq 6\) and \(K' \leq 20\). EROs are even more common in regions around high redshift quasars and radio galaxies with densities quoted as 10-100 times higher than in the field (Thompson et al. 1999; Smail et al. 1999; Graham & Dey 1996; Dey, Spinrad, & Dickinson 1995).

Because of their extreme faintness in the optical, very few spectra of EROs have been obtained. Graham & Dey (1996) took an infrared spectrum of ERO HR94 10 and found its redshift to be 1.44
based on the detection of one emission line, identified as Hα. This redshift has since been confirmed by Dey et al. (1999) with the detection of [OII]3727Å, although a follow-up Hα measurement shows the line to be much fainter than reported in the original paper. Soifer et al. (1999) took an infrared spectrum of EQ 0939+4713^1, from which they determine a photometric redshift ($z$~1.58 based on a spectral break), but they see no line features. Cimatti et al. (1999) have calculated photometric redshifts from 0.8 to 1.8 for 9 EROs based on near-infrared spectroscopy, but they measure no spectral lines and no continuum breaks. Finally, Liu et al. (1999) describe optical spectroscopy of several EROs in the field of a quasar at $z$=2.69. They detect emission lines, absorption lines, and continuum breaks in various objects, and they state that none of these objects are at the redshift of the quasar.

From the limited data, it seems that EROs are probably a heterogeneous population. ERO [HR94] 10 is clearly undergoing dust-enshrouded ($A_V$~1.8) star formation at a moderately high redshift ($z$=1.44), but emission lines have not been detected in the infrared for any other objects. Other EROs are best fit by old elliptical populations redshifted so that the 4000Å break causes the very red optical to infrared colors (e.g. Soifer et al. 1999). The nature of these objects (i.e. the presence of different amounts of star formation and dust and the existence of old stellar populations at high redshift) has implications for the star formation history of the universe.

In order to determine the characteristics of this population, more infrared spectroscopy is needed. We have taken low-resolution, infrared spectra of three EROs ([HR94] 14, PC 1247+3406B, and MG J1019+0535D) in order to find their redshifts and determine their star formation histories. [HR94] 14 was discovered by Hu & Ridgway (1994) in the field of a quasar at $z$=3.790. It has $K'_{s}=18.7$ and $(I - K') = 6.2$ and it is in the same field as [HR94] 10. Object PC 1247+3406B was discovered in the field of a quasar at $z$=4.897 by Soifer et al. (1994) and has $K_s = 19.4$ and $(R - K_s) > 5.5$. MG J1019+0535D was observed by Dey et al. (1995) in the field of a $z$=2.79 radio galaxy with $K_s = 18.26$ and $(R - K_s) > 7$. These objects were chosen because of their convenience on the night of the observations and because the papers in which they are described provide good coordinates.

2. OBSERVATIONS AND DATA REDUCTION

We observed three extremely red objects (EROs) using the Near Infrared Camera (NIRC) on the Keck I telescope (Matthews & Soifer 1994). We took photometric images in the J, H, and K bands and spectra covering $\lambda = 1.4\mu m - 2.5\mu m$ with spectral resolution of $R \sim 100$ and a slit width of 0'.52 (see Table 1). A spectrum of a calibration star was taken close in time and airmass to each ERO using the same spectrographic setup. Clouds were present during the observations, but the photometry in our fields was consistent with other measurements.

^1Soifer et al. (1999) refer to this object as Cl 0939+4713 B (from a cluster survey by Dressler & Gunn (1992)).
The telescope was dithered by ~ 6" along the slit during the spectral observations and sky frames were created by medianing together images in groups of five without aligning them. The spectral frames were warped so that the spectra and sky lines were straight and then rectified according to the formula given in the NIRC manual\(^2\). The ERO spectra were corrected for atmospheric effects by dividing by the stellar spectra. The standard stars were first divided by blackbody functions to remove their spectral shapes.

The photometric frames were dithered by 5" and sets of 9 unaligned images were medianed together to make sky frames. Aperture photometry was obtained using an annulus to subtract the sky level. For MG J1019+0535D, 4" diameter apertures were used to match the photometry given by Dey et al. (1995). For [HR94] 14, we do not have any photometry of our own and we used only the photometry of Hu & Ridgway (1994) which was taken in 3" diameter apertures. For PC 1247+3406B, Soifer et al. (1994) did not state the size of the aperture they used and have somewhat inconsistent total magnitudes quoted in their results. For this reason, we did not try to relate our photometric observations to theirs and we used only relative magnitudes from their paper. For all three, the spectra were flux calibrated by scaling to the photometric data (for PC 1247+3406B this was done using our K-band flux).

\section{RESULTS}

All three spectra are featureless with good continuum detections. The spectral slopes for all three objects are flat across the HK bandpass with no obvious breaks, which is consistent with the photometry. The 3\(\sigma\) line detection limit was \(3.1 \times 10^{-14}\) ergs\(^{-1}\) cm\(^{-2}\) for [HR94] 14, \(3.3 \times 10^{-14}\) ergs\(^{-1}\) cm\(^{-2}\) for MG J1019+0535D, and \(1.3 \times 10^{-14}\) ergs\(^{-1}\) cm\(^{-2}\) for PC 1247+3406B. For [HR94] 14 this detection limit is the same as for the spectrum of [HR94] 10 taken by Graham & Dey (1996) where Ha was detected at the 7\(\sigma\) level. A later revised measurement (Dey et al. 1999) showed that the flux of the Ha line is only \(3.3 \times 10^{-16}\) ergs\(^{-1}\) cm\(^{-2}\) and would not be detectable in our spectra. Therefore, we cannot put stringent limits on the star formation rates in these galaxies. The lack of any lines means that no direct redshifts were determined, but the slopes of the spectra, together with the photometry, can constrain the redshifts and other free parameters.

Our photometry of the EROs was supplemented with photometry taken from the papers in which they were discovered (see Table 2) and a Spectral Energy Distribution (SED) was created for each object using our spectra, our photometry, and the published photometry. We selected basic galaxy models from the SEDs of Bruzual & Charlot (1993) to compare to our data and applied a dust screen using the extinction curve from Cardelli, Clayton, & Mathis (1989). This reddening model was chosen because it provides an analytical function for the extinction from the infrared through the far-ultraviolet and is in good agreement with many other standard reddening curves.

\footnote{http://astro.caltech.edu/mirror/keck/reallpublic/inst/nirc/manual/Manual.html}
We used model SEDs with different ages and star formation histories, varied their redshifts and amounts of reddening, and fit them to our observed photometry and spectra. We used a $\chi^2$ minimization technique to find the parameters which provide the best fit to the SEDs. We used both the spectra and the photometry in the fits, and then eliminated cases that violated the photometric upper limits. The model SEDs all have Salpeter Initial Mass Functions with a mass range from $0.1 M_\odot$ to $125 M_\odot$. We used models with three types of star formation histories: an instantaneous burst of star formation, a burst lasting 1 Gyr, and a constant star formation rate. All three types included 12 models with ages from 1 Myr to 10 Gyr. The reddening was parameterized by the magnitudes of visual extinction, $A_v$. For each object, all 36 models were tested using redshifts up to 5 with a step size of 0.1 and $A_v$ up to 20 with a step size of 0.25.

Although the redshifts are not very strongly constrained, we are able to say something about the available parameter space for these galaxies. Most significantly, we can virtually eliminate the possibility that these EROs are at the same redshifts as the quasars in their fields. For all three galaxies, there is an acceptable fit in redshift versus reddening for each of the three models at most ages.

Other authors who have used similar methods to model ERO SEDs have used values of $A_v$ up to $\sim 2 - 3$ (e.g. Cimatti et al. 1999; Soifer et al. 1999). However, we had no compelling reason not to examine scenarios with high $A_v$. We found that there are fits to the data with large $A_v$ and that they have the same $\chi^2$ values as the low-$A_v$ solutions, although we cannot say at the present time whether these fits are physically reasonable. If better spectra of these objects reveal emission lines, a stronger statement could be made about the level of extinction in these galaxies. Very high values of $A_v$ may be valid because they are similar to those predicted for ultraluminous infrared galaxies. Values of nuclear $A_v$ for Arp 220 range from $\sim 8$ (Mazzarella et al. 1992) to $\sim 50$ (Sturm et al. 1996).

3.1. [HR94] 14

For most models the best fit to the [HR94] 14 SED is at either $z \sim 0.4 - 0.5$ with $A_v \sim 5 - 11$ or $z \lesssim 0.1$ with $A_v \sim 14 - 17$ (Figures 1 and 2). The $z \sim 0.5$ solution occurs for most models and seems to be the most favored — the best fit overall is at $z=0.4$, $A_v \sim 11$ with reduced $\chi^2=0.68$. The very low redshift, very high reddening case also fits for most of the models and is not differentiated from the $z \sim 0.5$ solutions for the youngest models. The $\chi^2$ values for all of the acceptable solutions are within $1\sigma$ of the best fit solution. It is, however, fairly unlikely that the $z \lesssim 0.1$ solution is valid because of the extreme nature of its derived properties. There is also a $1\sigma$ fit at $z \sim 2$ and $A_v \sim 0 - 1$ for the oldest models with no star formation. The two favored models match the two basic theories of EROs in general: the high-z, old elliptical and the low-z, dusty, star-forming galaxy. As we will see later, the $z \sim 2$ case requires stars that are older than the universe for the two oldest models,
which means that the lower redshift solution is even more favored.

Are our solutions for the possible redshifts reasonable? If [HR94] 14 is at a redshift of 2.0, it would have a luminosity of 10L* (rest frame R band), which would make it an unusually bright galaxy. At z=0.5 its luminosity would be 0.5L* (rest frame R band), its K-band magnitude would be M_K = -24.5, and its physical size would be ~ 4 kpc.

The redshift of the nearby quasar, z=3.790, is eliminated as a likely solution. The best possible fit for this redshift (Figure 3) has reduced \( \chi^2 = 4.6 \), which is more than 6σ away from the best fit. It is also clear that [HR94] 14 does not have the same redshift as [HR94] 10 (Graham & Dey 1996). [HR94] 10's redshift of z=1.44 is not in the allowed regions of the z/A_v space for any of the models. In order for the reddening to be as low as that calculated for [HR94] 10 (A_v=1.8), [HR94] 14 must have z~2 and very little star formation.

### 3.2. PC 1247+3406B

For PC 1247+3406B, the best fit for all of the models is either at z~ 0.9 – 1.2 or at z~ 1.5 – 1.8 (apart from one anomalous solution which is discussed at the end of this section). The best fit overall is at z=1.2, A_v = 1.0 with reduced \( \chi^2 = 0.34 \). There are a few models for which there are no solutions within 3σ of this minimum (all with old stellar populations), but there is a 1σ fit for most of the models.

Redshifts between 0.9 and 1.2 fit only for models with ages greater than \( \sim 50\)Myrs. These fits have A_v \( \sim 0 - 1 \) for the oldest models with no star formation, increasing for younger models and those with more star formation up to A_v \( \sim 2.5 \). All of these solutions have \( \chi^2 \) values within 2σ of the absolute minimum and many of them are within 1σ.

The solutions with redshift \( \sim 1.5 – 1.8 \) exist only for models with very young stellar populations — ages less than 5 Myrs for models with no ongoing star formation or less than 50 Myrs for models with star formation. These solutions are all within 2σ of the minimum \( \chi^2 \) and many are within 1σ. The A_v for these models starts at 2.0 and increases with younger models, those with more star formation, and those with higher redshifts up to A_v = 3.5 (Figures 4 and 5).

If PC 1247+3406B is at z=1 it would be a 0.5L* galaxy (rest frame B band) and at z=2 it would be a 5L* galaxy (rest frame R band).

For the youngest ages with all three star formation histories, a very high-z case appears, with z=4.5 and A_v \( \sim 2.5 \). However, we don’t trust the reliability of this case because the model SED is only consistent with the optical data due to the strong bump in the UV extinction curve near 0.2 \( \mu m \). With the amount of reddening necessary to fit the youngest models, the SED is very strongly affected by the shape of the reddening curve. Calzetti, Kinney, & Storchi-Bergmann (1994) have an extinction law with no UV bump, which would eliminate this solution, but this is artificial since they explicitly removed this feature from their extinction law. The extinction laws given by
Calzetti et al. (1994) for the Milky Way, Large Magellanic Cloud, and Small Magellanic Cloud are qualitatively similar to the one we used and would only result in small differences in the derived parameters. The fact that the strong dip in the SED occurs just at the wavelength where we have to date makes this solution even less likely and spectroscopy or photometry in the J band could rule it out.

The redshift of the nearby quasar (z=4.897) is close to those allowed by this anomalous solution. Although the best fit at that redshift is more than 4σ away from the minimum χ² (Figure 3), the fit would be even worse without the strong UV bump.

### 3.3. MG J1019+0535D

For MG J1019+0535D there is a strong degeneracy between low-z, highly-extincted solutions and high-z, low-extinction ones. For the oldest models with no star formation, the 1σ solutions lie in a continuum between z~0 – 0.1, A_v ~ 7 – 10 and z~1.8 – 2.2, A_v ~ 0 – 0.5. The most likely solution is z=0.1 which fits with the best overall χ² of 1.07 for one of the oldest models. As the age decreases and/or the amount of star formation increases, the high-z solution starts to disappear and the available 1σ parameter space shrinks towards the low-z end. As before, similar models with more star formation give equivalent solutions with higher reddening values, and they lose the high-z solutions earlier (Figures 6 and 7).

Once again the redshift of the nearby quasar (z=2.79) is eliminated as a solution for the ERO. The model shown in Figure 3 is the best fit for this redshift and it has χ²=3.83, which is more than 4σ away from the minimum. In this galaxy there is again the situation of a high-z case (z~2) at the youngest ages due to the effect of the UV-bump in the reddening curve on the SED. This time, however, the redshifts allowed by this solution do not match the redshift of the nearby quasar.

At z=2, MG J1019+0535D would have L= 6L_*, (rest frame R band), and at z=0.1 it would have L= 0.01L_*, (K band), M_K = -19.4, and a physical size of ~ 1 kpc, making it a very small, dim galaxy.

### 4. DISCUSSION

We find that it is very unlikely for any of the EROs to be at the same redshift as the quasar in their field. This redshift is eliminated at more than 6σ for [HR94] 14 and more than 4σ for MG 1019+0535D and PC 1247+3406B. For [HR94] 14 and PC 1247+3406B the fit would be even worse if not for the effect of the UV bump in the reddening curve.

One explanation for the over-density of EROs in the fields of quasars is that they are early galaxies physically associated with the quasars. However, no EROs, including ours, have been found at the same redshifts as their neighboring quasar. Dey et al. (1999) found that [HR94] 10 is at a
much lower redshift than its nearby quasar and Liu et al. (1999) found that all of the EROs in the field of a quasar at $z=2.69$ were at substantially lower redshifts. So, if the EROs are not physically associated with the quasars, what is the explanation for the overdensity in those fields? One possibility is that a foreground overdensity of galaxies magnifies the high-redshift quasar through weak lensing, leading to a bias in the selection of AGN (e.g. Thompson et al. 1999; Dey et al. 1999). This effect has recently been detected for normal, foreground galaxies and bright quasars (Norman & Impey 1999). However, it is premature for us to make any strong statements about the measurements of this overdensity or its explanation.

Another concern is the ages of the galaxies in the high redshift cases compared to the age of the universe. The highest redshift solutions for the EROs are $z \sim 2$. However, using our cosmology ($q_0 = 0.1, H_o = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$), the age of the universe at $z=2$ is only 2.7 Gyrs. This means that the two oldest models are not allowed at redshifts $\gtrsim 2$ for this cosmology. The main consequence of this limitation is that the $z \sim 2$ case becomes less viable for [HR94] 14 since this redshift is not as likely for younger models. A $\Lambda$ dominated universe provides additional time beyond $z \sim 2$ and eases this constraint.

In the models we tested, the extreme optical to near-infrared colors can be caused by two things — the 4000Å break and the cutoff from dust extinction. A uniformly old stellar population is needed for the 4000Å break to dominate, and this SED requires redshifts $\sim 1 - 2$ to match the colors of the EROs. Regardless of the age of the model, there is also a solution where the red color is caused by the cutoff from extinction. In this case there is a minimum amount of dust needed, $A_v \sim 1 - 5$ depending on the object, and a degeneracy between models with a large amount of dust at low redshifts and ones with less dust at higher redshifts (up to $z \sim 2$).

5. CONCLUSIONS

We have observed the continuum flux for three extremely red galaxies and used this data to constrain their physical state. Fitting to galaxy models offers some constraints on the state of the system; the solutions are restricted a few possible redshifts for each object and each of these redshifts is only compatible with narrow ranges of reddening and age. We found that there are solutions with large $A_v$ that fit just as well as the low-$A_v$ solutions and we cannot say at the present time whether these fits are physically reasonable. The most striking result is the virtual elimination of the possibility that these galaxies are at the redshifts of the quasars they were discovered near. It will take more optical photometry, or much better spectra that could detect lines, to determine further parameters for these galaxies.

Data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by
the generous financial support of the W. M. Keck Foundation. We would also like to thank Joel Aycock for his help in making these observations.
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This preprint was prepared with the AAS LaTeX macros v5.0.
Fig. 1.— Plots of contours of equal $\chi^2$ for [HR94] 14 versus redshift and reddening. The point of minimum $\chi^2$ is marked with a box for each case and the contours are at 1σ, 2σ, 3σ, 4σ, and 5σ levels. The three panels show models with three different combinations of $z$, $A_V$, age, and star formation model that fit this object and are representative of all of the fits. The fit in the upper left has the lowest reduced $\chi^2$ of any fit ($\chi^2=0.68$) and the other two have $\chi^2 \sim 1.2$. 
Fig. 2.— The SED for [HR94] 14 is plotted here along with four models that fit it. The long, solid bar is the spectrum binned to show just the continuum, the short horizontal bars are the photometric points, and the point with an arrow is the upper limit at B. The models plotted correspond to the three fits shown in Figure 1, plus the solution at $z=2$. Although this redshift is not the best fit for any model, it is allowed for the oldest models with similar $\chi^2$ to the best fits. The model SEDs are extremely similar to each other even though they have extremely different parameters.
Fig. 3.— The best fitting SEDs for all three objects at the redshifts of the quasars. The spectrum for PC 1247+3406B is drawn with a dashed line for visibility. For [HR94] 14 this solution is ruled at at greater than 6σ and for MG J1019+0535D and PC 1247+3406B the fits are ruled out at greater than 4σ. For [HR94] 14 and PC 1247+3406B, the strong bump seen in the blue end of the models is the UV bump in the extinction curve, and without this feature the fits would be even worse.
Fig. 4.— The same as Figure 1 for PC 1247+3406B. The fit in the upper left has the lowest reduced $\chi^2$ of any fit ($\chi^2=0.34$) and the other two have $\chi^2 \sim 1$. The fits are clearly very tightly constrained for this object.
Fig. 5.— The same as Figure 2 for PC 1247+3406B. The spectrum is shown with a thick dashed line in this case to differentiate it from the K-band photometry point and the SEDs are plotted for the three cases shown in Figure 4. Again, the model SEDs are extremely similar even though they have widely varying parameters. The bumps at the blue end for two of the models are due to the UV bump in the reddening curve (see §3.2).
Fig. 6.— The same as Figure 1 for MG J1019+0535D. Notice the continuum of parameter space within 1σ for the oldest model. The model in the upper right has the lowest reduced $\chi^2$ of any fit ($\chi^2=1.07$) and the other two have $\chi^2 \sim 1.1 - 1.3$. 
Fig. 7.— The same as Figure 2 for MG J1019+0535D. The three models plotted are from the fits in Figure 6 and again are all very similar. The bump at the blue end of the model at age 1 Myr is again due to the UV bump in the reddening curve. This is the anomalous solution for the youngest models at $z \approx 2$ mentioned in the text (see §3.3).
<table>
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<tr>
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<th>Band</th>
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Table 2. Apparent Magnitudes

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<sup>a</sup>Hu & Ridgway 1994

<sup>b</sup>Soifer et al. 1994

<sup>c</sup>Dey, Spinrad, & Dickinson 1995