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OBSERVATIONS OF DEEP 2 MICRON SURVEY GALAXIES: PRIMEVAL GALAXY CANDIDATES[1]

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ABSTRACT

We have made *BVRIJHK* photometric and optical spectroscopic observations of two red galaxies located during a deep 2 μm imaging survey of the sky and suggested to be a new extragalactic population, possibly primeval galaxies. Based on the optical spectroscopy and the photometric data, these red objects appear to be very luminous galaxies at $z = 0.8$. They have visual–IR colors characteristic of a galaxy dominated by an old stellar population, similar to that of a current-day elliptical, but they have UV–optical colors and 4000 Å break amplitudes indicating a bluer main-sequence turn-off. The presence of two galaxies with luminosities similar to giant ellipticals in only 10 arcmin^2 of sky is very improbable (1 in 10^4) and could indicate strong selective luminosity evolution of these galaxies, since only two to three galaxies per square degree would be expected at this luminosity between $z = 0$ and 1.5. Despite being as luminous as brightest cluster galaxies at the same epoch, they appear to be isolated with no indication of rich clusters associated with them.

These *BVRIK* images were used to look for sources with flat spectral energy distribution in a 6 arcmin^2 area with $R < 22$. Two sources have spectra which are nearly flat from V to K but have a flux decrement into the B band which is too large to be the Balmer edge in a star-forming galaxy. A low signal-to-noise ratio optical spectrum of the more extreme object (130527.1+294633.5) reveals a very blue continuum with no strong emission lines suggesting $z > 1$. We suggest that this could be a star-forming galaxy at a redshift of 4 with the Lyman limit between the B and V bands and possible Lyman-alpha forest absorption beginning at 5800 Å. Additionally, we have found three sources with blue spectral energy distributions. These sources are presumably dominated by the light of a young stellar population of $z < 3$.

Subject headings: galaxies: evolution — galaxies: photometry — infrared: sources

I. INTRODUCTION

In Elston, Rieke, and Rieke (1988, hereafter Paper I) we conducted a deep 2 μm imaging survey of the sky to locate high-redshift galaxies in an unbiased way. Near-IR–selected samples of galaxies like these should be useful for studies of galaxy evolution and cosmology at high redshift since near IR emission will not be as strongly affected by evolution of the stellar population as optically selected samples. Also, it may be possible to locate types of objects which emit very little flux in the optical due to dust, Lyman limit absorption, or Lyman-alpha forest absorption.

In Paper I the data were analyzed using an $R-K$ color-magnitude diagram to locate different types of objects. These observations showed the presence of a locus of galaxies with colors and magnitudes similar to those expected for elliptical galaxies with $z = 0.2$–1. Given that the $R-K$ colors of galaxies should be monotonic and relatively insensitive to galaxy type until $z = 1$ and that large elliptical galaxies are both the reddest and most luminous galaxies, we argued that such a locus of galaxies is expected and should form a "red envelope," with galaxies occurring on only one side of the locus.

In Paper I we noted two nonstellar sources about 1.5 mag above the red envelope. While the colors and magnitudes of these sources are similar ($K = 17$, $R-K = 5$) to those of radio galaxies near $z = 1$, we argued that the density of such luminous galaxies (i.e., brightest cluster galaxies) should be about 100–1000 times lower than that observed. We thus concluded that these were a new type of extragalactic object. Given the large but highly uncertain number density, we suggested that these were good candidates to be high-redshift galaxies during a luminous star-forming phase, and we argued that all the properties were consistent with but not sufficient to prove a primeval galaxy (PG) interpretation. In this paper we present extensive new observations of these two objects.

We have also used the *BVRIK* images to look for flat spectrum sources, and we have located galaxies with SEDs which are dominated by young stellar populations at $z < 6$. In one case we have obtained an optical spectrum which suggests $z > 1$, and a spectral break suggests $z \approx 4$.

II. OBSERVATIONS

Since PGs should have a very distinctive spectral energy distribution (SED) (Partridge and Peebles 1967; Meier 1976) we obtained *BVRIJHK* photometry of the red PG candidates from Paper I. The MMT liquid helium–cooled InSb single-channel photometer was used to make *JHK* photometric observations. An 8".7 diameter aperture was used with a 10" chopper throw. Photometric calibration was based on observations of standard stars from Elias *et al.* (1982). Independent observations were obtained on two nights in each of the colors

[1] Observations reported here were obtained with the Multiple Mirror Telescope, a facility operated by the Smithsonian Institution and the University of Arizona.

TABLE 1

LUMINOUS RED GALAXIES

Band	130526.6+294646	130528.0+294624	$z = 0.77$ E Galaxy
K	17.01 ± 0.07	16.86 ± 0.07	...
$H-K$......	1.03 ± 0.14	1.31 ± 0.19	0.80
$J-K$	1.88 ± 0.12	1.74 ± 0.14	1.85
$R-I$.......	1.54 ± 0.25	1.36 ± 0.22	1.38
$R-K$......	4.80 ± 0.17	5.08 ± 0.14	4.94
$V-R$	1.44 ± 0.21	0.92 ± 0.18	1.74
$B-V$	1.36 ± 0.20	0.84 ± 0.22	2.11

and checked for consistency. The combined data are given in Table 1. We shall reference all photometry to a 9″ aperture.

BVRI photometry in "nearly Mould" filters was obtained at the Steward Observatory 2.25 m telescope using a TI CCD. Fluxes were measured in a 9″ diameter circular aperture using IRAF[2] APPHOT. The photometry was transformed to the standard system using the M67 calibration of Schild (1983). Typically four frames were taken in each color and checked for consistency. The final photometry of the red PG candidates is given in Table 1.

While there is no indication that PGs should have strong UV emission lines for an extended period of time (Hartman *et al.* 1988), we obtained optical spectra since such observations could provide the best proof of a lower redshift object. Long-slit spectra were obtained using a 1″.5 slit on the MMT during two observing runs. The spectra were obtained in the red (5000–8000 Å) since such spectra would give the best chance of finding a 4000 Å break at $z = 1$ which would be consistent with the $R-K$ colors. Two 1 hr exposures were taken using the FOGs spectrometer with a 150 l mm^{-1} grism, which gave 10 Å resolution from 4500 Å to 8500 Å. Additionally, three 1 hr spectra were taken using the Red Channel spectrometer with a 300 l mm^{-1} grating which gave 7 Å resolution from 5000 Å to 8000 Å. Flux calibration was applied using standard stars from Stone (1977). The FOGS spectra and the Red Channel spectra were compared and found to be consistent. The 5 hours of optical spectra for each of the red objects were combined and are presented in Figure 1. To study how the optical was connected to the near-IR, two 1 hr spectra were taken from 7000 Å to 10,000 Å using the 300 l m^{-1} grating with the Red Channel spectrometer, but these data were useful only below 9500 Å, due to atmospheric emission and absorption.

[2] IRAF is distributed by the National Optical Astronomy Observatories, which is operated by Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

III. DISCUSSION

a) Galaxies above the Red Envelope

The spectral energy distributions of the sources are presented in Figure 2. From the SEDs it does not appear that these sources are PGs. The near-IR is rather flat in both sources, rising very slowly from J to K, and the optical from B to R is also rather flat, but the rise from the optical to the near-IR is not as sharp an edge as would be expected in a PG (Partridge and Peebles 1967; Meier 1976). Since the Lyman limit edge in a PG could be softened by Lyman-alpha forest absorption between Lyman-alpha and the Lyman limit of the PGs, the comparison to model PG SEDs is not certain, but in this section we will show that the optical spectra and SED are consistent with a luminous red galaxy at $z = 0.8$.

The optical spectra in Figure 1, while being of rather low

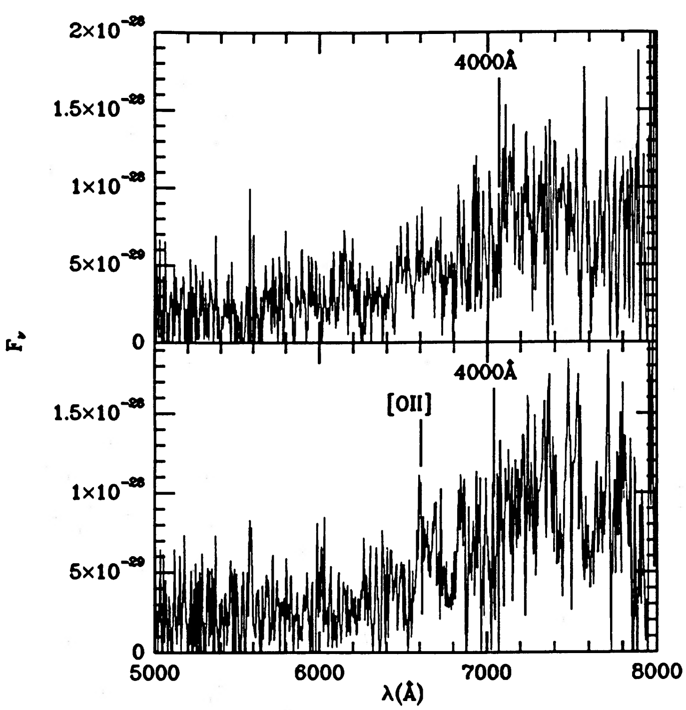

FIG. 1.—Spectra of 130526.6+294646 and 130528.0+294644 derived from 5 hours of integration at the MMT. While noisy, they do seem to have spectral breaks near 7000 Å. Assuming that these breaks are the 4000 Å break gives redshifts of 0.8 which are confirmed by the spectral energy distribution.

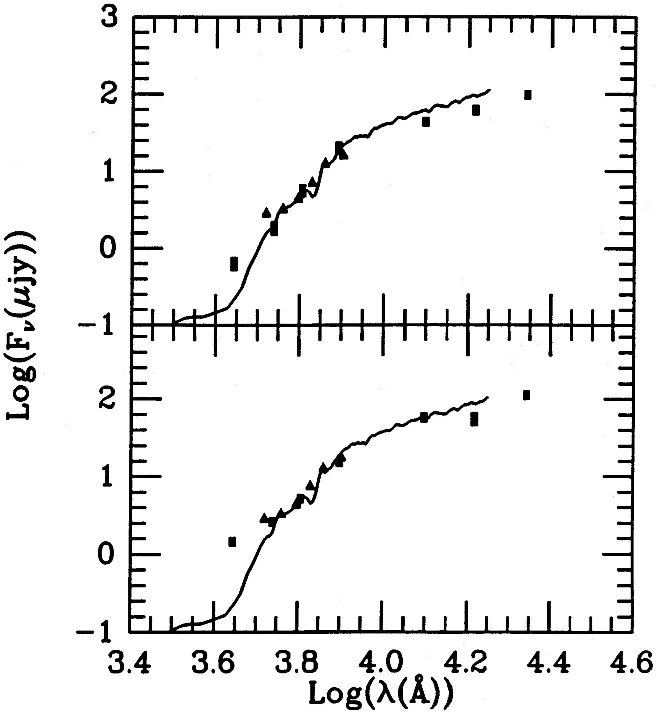

FIG. 2.—The optical IR SEDs of 130526.6+294646 and 130528.0+294644. The redshifted SED of a $z = 0.77$ elliptical galaxy from Coleman, Wu, and Weedman (1984) is shown by the solid line. The squares are the *BVRIJHK* photometry with the 1 σ errors given by the height of the box. The triangles are the optical spectra binned into 500 Å regions. The SEDs of these objects closely match those of the current-day elliptical in the visual to IR. The UV to visual of these objects is bluer than the current-day E galaxy indicating a main sequence turnoff mass slightly higher than 1 $M_\odot$.

signal-to-noise ratio, do indicate a spectral break. In 130526.6+294646 the break occurs at 7072 ± 10 Å. The break amplitude is 1.71 ± 0.10 as defined by Hamilton (1985). 130528.0+294624 has a break near 7090 ± 20 Å with an amplitude of 1.56 ± 0.10. If we assume that this is the 4000 Å break, then redshifts of 0.768 ± 0.003 and 0.773 ± 0.005 are found for 130526.6+294646 and 130528.0+294624, respectively. We also looked for additional features in the spectra and found none in 130526.6+294646. In 130528.0+294624 we found a weak emission line, in a region free from strong night sky emission, at 6608 ± 3 Å which could be 3727 Å at $z = 0.773 \pm 0.0004$. Thus the redshift of 130528.0+294624 looks rather secure at 0.773, but 130526.6+294646 is uncertain since there is only one feature and we do not know with certainty that it is the 4000 Å break.

In Figure 1 we have also plotted the spectrum of an elliptical galaxy taken from Coleman, Wu, and Weedman (1980) shifted to the redshift given by the spectral break. As can be seen the agreement from the *R* band to *K* is rather good. This can be used as further confirmation that the observed break is at 4000 Å. The near-IR colors are dominated by giants, whose properties are rather insensitive to the main-sequence turnoff mass and are thus reasonable redshift indicators. Table 1 gives the expected colors of a current day elliptical galaxy at $z = 0.77$. 130526.6+294646 has IR colors very similar to those of a $z = 0.8$ galaxy. The $J-K$ colors of 130528.0+294624 are near those of a $z = 0.8$ galaxy, but the H flux is 2 σ below the expected color. While the red portion of the SED agrees well with a current-day elliptical, the blue portion of the SED and the break amplitudes are different.

Typical break amplitudes in current epoch E galaxies are about 2 (Hamilton 1985). A break amplitude of 1.6 implies a younger component in the stellar population than is found in current-day E galaxies. Similarly, the $B-V$ and $V-R$ colors are very blue compared to a current-day elliptical indicating more recent star formation. 130528.0+294624 has UV colors similar to those of a blue spiral galaxy at $z = 0.8$ and an [O II] 3727 with an equivalent width of 10 ± 5 Å is possibly observed (Coleman, Wu, and Weedman 1980). 130526.6+294646 has redder colors and a larger break amplitude like those of a red spiral galaxy. Thus, these objects have composite spectra; they are dominated by a population like an old E galaxy in the red and by a younger stellar population in the blue.

By comparing the observed SEDs with model galaxy SEDs by Bruzual (1983) it appears that a 14 gyr "C" model reproduces the bulk of the observed SED, from the *R* band to *K*. A problem arises because the 4000 Å break amplitude and the blue optical colors do not match the model well and suggest a main-sequence turnoff near early G types to middle F (Bruzual 1981). Since published model SEDs become both bluer in their optical–IR colors and UV–optical colors simultaneously (Struck-Marcell and Tinsley 1978; Bruzual 1983), it appears that no conventional galaxy model with a nonrevolving giant branch can match the observed SEDs of these objects. Color evolution similar to that observed here is noted in a sample of red cluster galaxies by Lilly (1987), and he models the continued redness of the optical–IR colors as being due to an enhanced AGB population. Without model SEDs which include evolution of the giant branch population, it is difficult to predict the actual age of the stellar population, but a main-sequence turnoff slightly above 1 $M_\odot$ would match both the break amplitude, blue colors, and the appearance of a red AGB (Iben and Renzini 1983). Such a main-sequence turnoff would imply a formation epoch about 4 Gyr before $z = 0.8$ ($z_{\rm form} = 2$ for $H_0 = 50$, $q_0 = 0.1$; $z_{\rm form} = 10$ for $H_0 = 100$, $q_0 = 0.1$).

We combined the optical CCD images to form an image with a 3 σ *R* detection limit of about 27 mag arcsec^2 (Fig. 3 [Pl. 4]). As can be seen in this image these objects are clearly extended. The GASP surface photometry program was used to measure the surface brightness profiles of these objects as in Cornell *et al.* (1986). The profiles are shown in Figure 4 and are fitted by an $R^{1/4}$ law and an exponential disk outside of the seeing-dominated region. The fit parameters for an exponential disk seem plausible with a rest frame *B* central surface brightness of 20.5 and a scale length of 2.5 kpc (Freeman 1970). The $R^{1/4}$ law fit yields a half-light radius (r_e) of 10 kpc and a very bright half-light *B* surface brightness (B_e) of 19.7 (Kormendy 1977). With several magnitudes of luminosity evolution, to reduce the surface brightness further, either fit could agree with current epoch disks or spheroids. All we can conclude is that the profiles are consistent with an $R^{1/4}$ law or an exponential disk, but given the data, we cannot tell which. An examination of the region surrounding these galaxies does not reveal any concentration of fainter galaxies near them. Since the composite image (Fig. 3) reaches at least 3 mag fainter than these galaxies, we can conclude that there is no rich cluster associated with either of them.

Finally, it is worth considering why these objects would be found in our survey of only 10 arcmin^2. Their *K* magnitudes of 16.8 compare closely with the average found for bright radio galaxies at the same redshift, $K = 16.4$ (Lilly, Longair, and Allington-Smith 1985; Lebofsky and Eisenhardt 1986). Since

PLATE 4

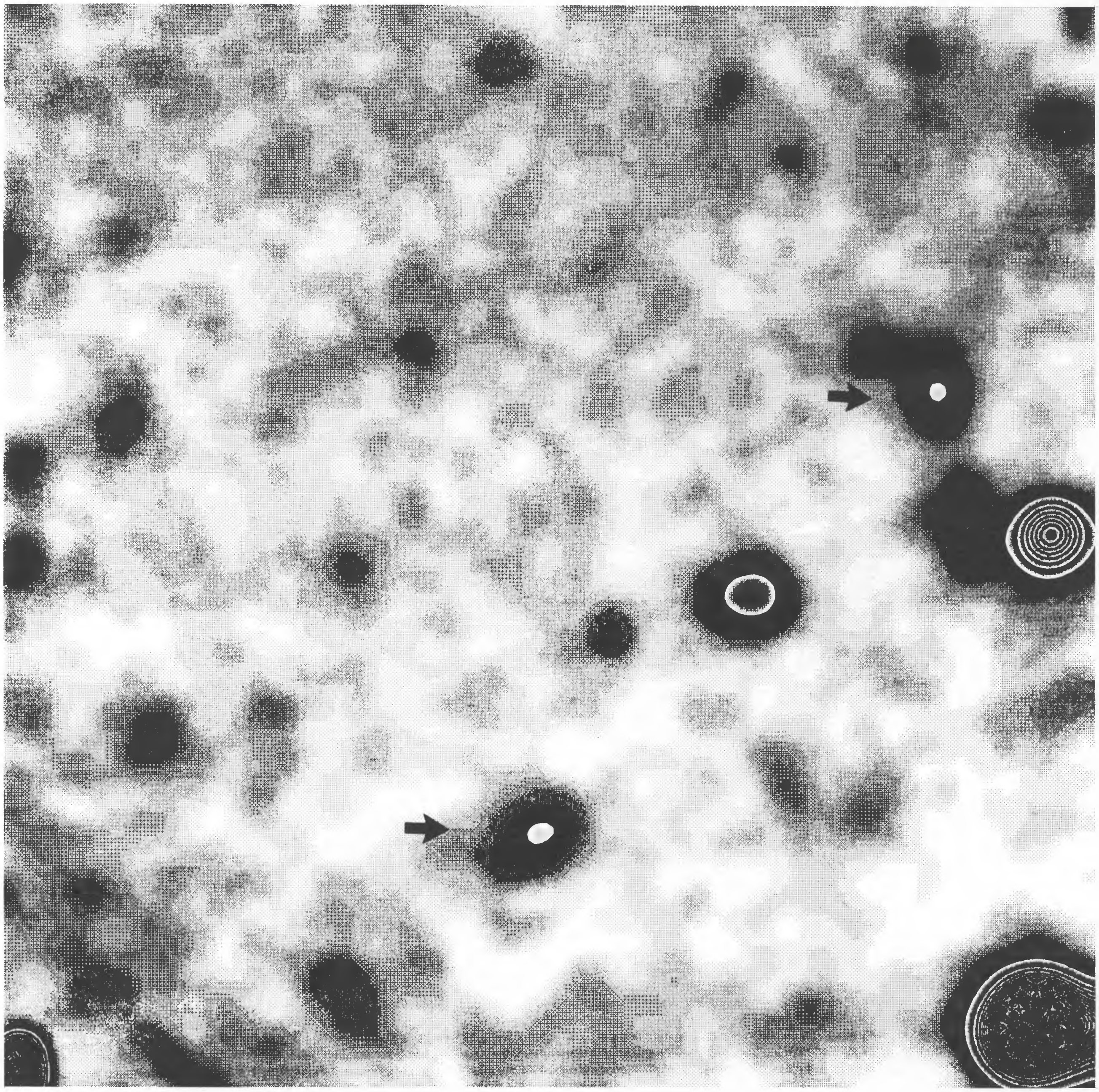

FIG. 3.—Optical image of 130526.5+294646 and 130528.0+294624. The image is a composite of *BVRI* frames and reaches a 3 σ detection limit of about 27 mag arcsec^2 in *R* and is 1′ on a side. Even though these images reach 4 mag below the objects, we see no concentration of galaxies near them, indicating they are in a poor environment.

ELSTON *et al.* (*see* **341**, 82)

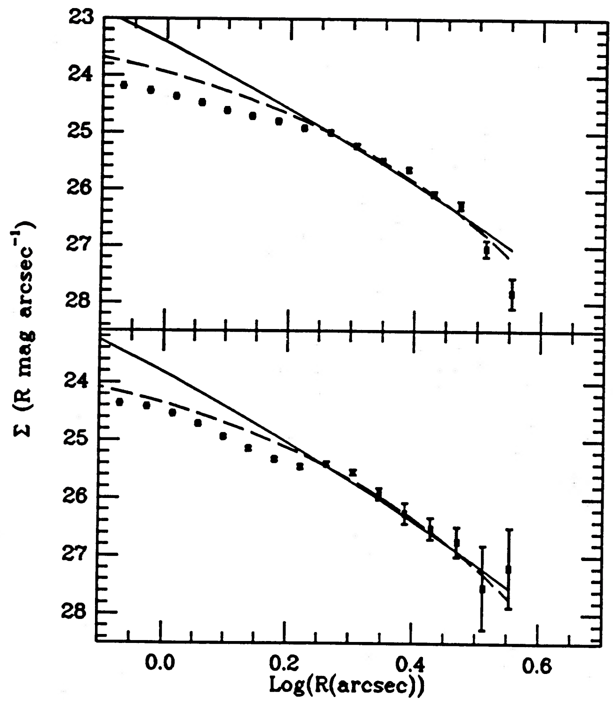

FIG. 4.—Surface photometry of 130526.6+294646 and 130528.0+294624. The objects are very extended. The solid lines indicate an $R^{1/4}$ law fit, while the broken lines indicate an exponential disk fit.

these radio galaxies are of similar luminosity to brightest cluster galaxies (BCGs) (Spinrad 1986) we can assume that the two new objects have luminosities similar to BCGs and giant ellipticals. This conclusion results in an interesting interpretation of our $R-K$, K diagram if we associate the $R-K$ color with galaxy redshift. In this case the red envelope of normal galaxies with $R-K$ of about 5 lies 1.5 mag fainter than the two luminous galaxies, indicating that the next brightest galaxies at the same redshift have luminosities close to L_*. From the luminosity function of Davis and Huchra (1982), one would expect about $1000L_*$ galaxies per square degree between $z = 0.5$ and 1.0, and in fact we observe this density of galaxies along the red envelope for $4 < R-K < 5$. However, the luminosity function of Davis and Huchra (1982) predicts only three to four galaxies per square degree for $0 < z < 1.5$ ($q_0 = 0.5$) and with luminosities 1.5 mag brighter than L_*. Thus, the probability of our finding two such galaxies is about 1 part in 10^4.

Given that our two galaxies are near each other on the sky and appear to be at similar redshifts, one could argue that they are correlated and that the probability of finding them should be the probability of finding a poor cluster with two BCGs. At redshifts up to $z = 1$ ($q_0 = 0.5$), about 45 clusters are expected per square degree (Gunn, Hoessel, and Oke 1986), of which about 20% will contain giant ellipticals (Bahcall 1977). From this alternative statistic we would expect about nine BCGs per square degree to $z = 1$ and one chance in 40 of finding one such galaxy in our survey. However, van der Bergh (1975) estimates that 93% of giant ellipticals lie in rich clusters, whereas we know that the two objects under discussion must be in poor clusters if any. The probability of a giant elliptical in a poor cluster is small, probably <8% (Bhavsar and Barrow 1985). Thus, there is about one chance in 400 that we would have found one such galaxy in our survey. Bhavsar and Barrow (1985) argue that the incidence of giant ellipticals in groups is consistent with random statistics of the galaxy luminosity function. In this case, the probability of two such galaxies in a single group or poor cluster is the square of the probability of one, and the likelihood of our finding two giant ellipticals in our survey is 1 part in 10^4, whether they are in a single group or cluster or in separate ones.

Both galaxies lie very close to the expected $R-K$ color for a nonevolving galaxy at $z = 0.8$. In contrast, most galaxies known near this redshift evidence for significant evolution in this color and are bluer than the two galaxies under discussion (Lilly and Longair 1984; Lilly, Longair, and Allington-Smith 1985; Eisenhardt and Lebofsky 1987). Since most other $z = 0.8$ galaxies were discovered through their strong radio emission or because they lie in rich clusters which require evolution of the UV luminosities to provide sufficient contrast on the sky to have been detected (Couch *et al.* 1984), their blue colors may result from their environments and selection. Thus, the two galaxies under discussion may not be as exceptional in this regard as the existing data would imply.

The newly discovered galaxies appear to be similar to ones discovered by Hamilton (1985) in a survey that selected galaxies by red color in the optical and near-infrared. He used photographic plates to image approximately 5 square degrees and obtained spectrophotometry of red, extended objects that did not lie in rich clusters. In common with our two galaxies, the galaxies so discovered are distinguished by H and K breaks that are nearly as strong as those for nonevolving galaxies. Curiously, the two highest redshift objects in his survey, SA 68:2 7024.0 and 6947.0, are both at redshift 0.78 and lie within 13″ of each other on the sky. This pair of galaxies is incredibly similar to the pair we have discovered, which are at $z = 0.77$ and lie within 29″.

Either we were exceptionally lucky in finding these two galaxies, or the density of such objects on the sky is not predicted accurately by our present understanding, or a combination of both. The first possibility will be addressed by surveying a larger area of the sky; fortunately, the development of larger format infrared arrays will facilitate this work. The second possibility might result if there is a change in the luminosity function at $z > 0.5$, i.e., there is an increase in the percentage of very high luminosity galaxies. Such evolution of the near-IR luminosity is not easily understood since the IR luminosity depends most strongly on the number of giants (Tinsley 1980), which is determined by the rate at which stars leave the main sequence. Large variations in the luminosity evolution of galaxies would imply large variations in the initial mass function (IMF) from object to object. In particular one needs a large high-mass bump in the IMF to make a galaxy overluminous in the past.

The fact that the high-redshift, red, noncluster galaxies found so far seem to come in pairs at projected separations of <100 kpc suggests a means of getting a bump in the IMF. They could be postinteractive systems. If so, the high luminosities could result from stars created in interaction-triggered starbursts; since the colors and depth of the H and K break imply an old population, the starburst would have been initiated at very large redshift, $z > 3$. So that the galaxies luminosities would decay relatively rapidly from $z = 0.8$ to the present epoch, the IMF of the interaction-triggered starburst would need to contain a large proportion of massive stars.

Additionally, there are objects from Paper I, from the tip of the galaxy locus, which are of interest. One object (130527.06 + 294354.9) has been confirmed in the near-IR with the MMT. It has $K = 17.95 \pm 0.20$ with an $R-K$ color of 5.9 ± 0.4. At these faint levels we cannot tell if this source is stellar or extended, but we believe it is not an extreme halo dwarf since it has a $V-R$ color of 1.46 ± 0.5. With $K = 18$ and $R-K$ of 6, this object is about as far above the red envelope as the sources considered here. This object could well be a further example of the type of galaxy described in this paper but at $z = 1.2 \pm 0.2$. Alternatively, it is very near the most extreme $R-K$ color which can be achieved by a galaxy at any redshift and could be a PG at very high redshift ($z > 6$) as discussed in Paper I.

Now that these objects appear to be eliminated as PG candidates, we can place limits on models for high-redshift PGs ($z > 6$). In Paper I we related the luminosity of a PG to the duration of the initial burst. From the lack of PGs with K magnitudes brighter than 17.5 in 10 arcmin^2, we can place limits on the initial burst duration for large elliptical galaxies. From our models, it would appear that PGs with an initial burst of 10^8 yr are not common at $5 < z < 20$ ($q_0 = 0.5$ and $h = 1$). For longer bursts of 10^9 yr (lower luminosity PGs) we can place limits only out to $z = 5$. Similarly, for very luminous short burst PGs with $T = 10^7$ yr we can eliminate those models with $z > 10$. At lower z the density of objects is too small to be certain of detecting a short burst PG. For an alternative set of PG model constraints, to which these data can be applied, see Boughn, Saulson, and Uson (1986).

b) Blue Star-forming Galaxies

A large population of galaxies with blue optical colors is known to exist at faint levels (Tyson 1988 and references therein). It is also well known that blue galaxy colors are indicative of active star formation (Struck-Marcell and Tinsley 1978; Bruzual 1983). Stellar population models with constant star formation rates and an evolving giant and AGB population maintain their blue colors for less than a few times 10^8 yr (Wyse 1985; Chokshi and Wright 1987). Thus, we shall consider a population formed during the last 10^8 yr to be a young population since it will produce a flat SED. Any population older than a few times 10^9 yr will be considered an old population because its red SED should be easily distinguished from that of a young population.

The major difficulty with understanding the blue objects is that the UV to optical portion of the SED can be completely dominated by a small young stellar population even if there is a much larger old population ($M_{\text{young}} \leq 1\% M_{\text{old}}$). As a result, UV and optical measures cannot determine whether the blue colors represent a major star-forming phase. Since the SED of an old population peaks in the near-IR, the addition of K photometry can place a more significant lower limit on the mass of the young population. From combining Bruzual SEDs with ages of 5×10^7 yr and 4×10^9 yr, it seems that an $R-K$ color less than 2 at rest or 3.5 for objects with $z > 1$, places a firm lower limit on the young stellar mass, requiring it to be more than a percent of the old stellar mass. This is a fairly general conclusion for a large range of stellar population ages and suggests that reasonable limits can be placed on a young population by K photometry.

Depending on its redshift the observed SED of a star-forming galaxy will appear rather different. Basically, the SED of a star-forming galaxy is flat except for the prominent spectral breaks at the Balmer edge and the Lyman limit (Bruzual 1983). From $z = 0$ to $z = 1$ the Balmer edge will fall in the optical producing a flux decrement of about a factor of 1.5 or less. From $z = 1$ to $z = 3.5$ the optical portion of the SED will be smooth since no major flux decrement lies in the optical. Finally, from $z = 3.5$ to 7 the optical SED will have a large spectral break due to the Lyman edge. Since we have six band photometry we can use the break features to try and constrain the redshifts of the objects.

To investigate the blue population, we used the *BVRIK* images of 6 arcmin^2 of sky obtained during these follow-up observations. We selected all sources brighter than 22 at R but which were not detected or were weakly detected at K ($K < 18.5$ 3 σ for galaxies). In such a source the K flux is constrained to be less than about 5 times the R flux. This yielded seven extended sources, of which one was not detected at K because of source overlap in the object and offset frame in the K image. Photometry of the blue galaxies is presented in Table 2. U photometry has been kindly supplied by D. Koo (1988) from his 4 m photographic plates.

The sources all have blue SEDs from V to K but seem to fit into two groups depending on the $B-V$ color. The first group has very red $B-V$ colors ($B-V > 1$) and consists of 130530.6 + 294608 and 130527.1 + 294634. The second group has bluer $B-V$ colors and consists of 130525.6 + 294454, 130528.5 + 294501, and 130519 + 294622. 130518.5 + 294633 seems to be redder across its entire optical SED; although the photometric errors make it difficult to classify, it is probably a spiral galaxy. We shall consider the sources with the prominent spectral break between B and V first.

i) *Candidate Star-forming Galaxies at z = 4*

In this section we will discuss two objects which based upon extensive photometry but limited spectroscopy appear to be good candidates to be luminous star forming galaxies at a redshift of about 4. Final confirmation of their nature will have to await a moderate signal-to-noise ratio spectrum extending into the blue. We present them now since they appear to have

TABLE 2

BLUE IR-SELECTED GALAXIES

R.A.(1950)	Decl.(1950)	$U-B$[a]	$B-V$	$V-R$	R	$R-I$	$R-K$
$13^h5^m30^s.55$......	29°46′ 8″.1	-1.03 ± 0.25	1.02 ± 0.13	0.27 ± 0.14	21.02 ± 0.13	0.51 ± 0.16	2.96 ± 0.34
13 5 27.09......	29 46 33.5	-1.35 ± 0.35	1.40 ± 0.17	0.18 ± 0.18	21.72 ± 0.16	0.59 ± 0.18	2.63 ± 0.8 (<3.2)
13 5 25.55......	29 44 53.9	...	0.53 ± 0.16	0.31 ± 0.18	21.96 ± 0.16	...	<3.5
13 5 28.46......	29 45 1.3	...	0.39 ± 0.16	0.27 ± 0.18	22.00 ± 0.16	...	<3.5
13 5 18.45......	29 46 33.4	...	0.74 ± 0.28	0.90 ± 0.28	21.82 ± 0.18	...	<3.3
13 5 19.34......	29 46 22.1	...	0.03 ± 0.25	0.66 ± 0.31	21.82 ± 0.23	...	<3.3

[a] U photometry is from Koo 1988.

SEDs which are not consistent with known galaxies and should be of interest even if they are not at a redshift of 4. Additionally, we present them to illustrate that the simple notion of what the SED of a PG should look like (Partridge and Peebles 1967; Meier 1976) may be in error since these objects possess neither a strong Lyman-alpha line nor a very large flux decrement at the Lyman limit.

From the photometry 130530.6+294608 and 130527.1+294634 seem to have very flat SEDs from V to K indicating they are dominated by star formation; however, they have a strong spectral break between B and V (Fig. 5). 130527.1+294634 is of particular interest since we have obtained an optical spectra of it. The spectrum is flat and featureless from 5000 to 8000 Å (Fig. 6), possibly with a weak break at 5800 Å. From the absence of emission lines but the presence of a very blue SED we can probably rule out redshifts below 1.2, since Hα, [O III] 5007, and [O II] 3727 are commonly present in galaxies with optical to IR colors this blue with equivalent widths greater than 40 Å and should have been detected. This suggests that the spectral break cannot be the Balmer edge but must rather be the Lyman Limit at $z = 4$.

We can also use the SED alone to consider what redshifts these star-forming galaxies could have. In Figure 5 we compare the SEDs to that of a star-forming Im galaxy from Coleman, Wu, and Weedman (1980). These objects are as blue from V to K as an Im galaxy at any redshift (Coleman, Wu, and Weedman 1980), but the $B-V$ colors of 1 and 1.4 are redder than an Im galaxy at any $z < 3$. This implies that the spectral

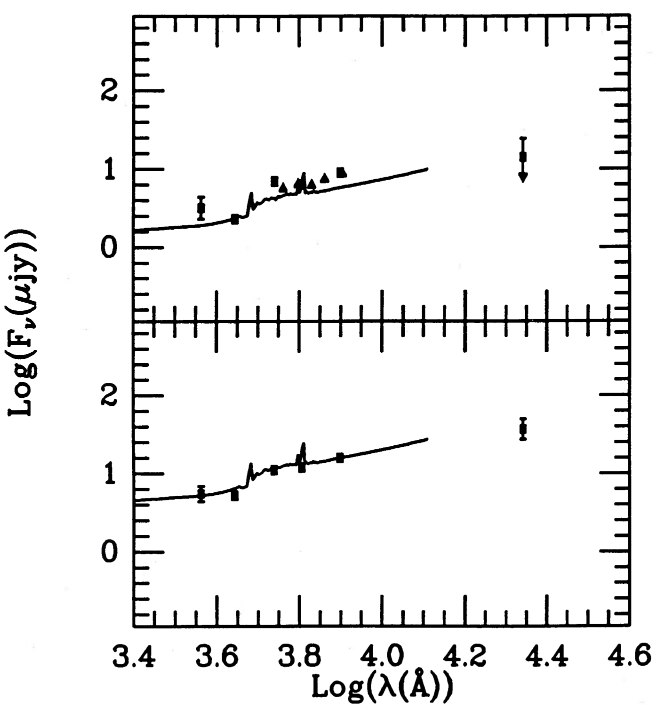

FIG. 5.—Spectral energy distributions of 130527.1+294634 (*top*) and 130530.6+294608 (*bottom*). Square points are *UBVRIK* photometry, while triangles are points derived from the optical spectra, *U* photometry has been supplied by Koo (1988). The solid line is an Im galaxy taken from Coleman, Wu, and Weedman (1980). 130530.6+294608 can be fitted approximately by an Im galaxy with $z = 0.2$, but the photometry indicates that the break between *B* and *V* has too large an amplitude to be the Balmer limit. 130527.1+294634 clearly has too large a break to be the Balmer limit, and we suggest that this may be the Lyman limit.

break between B and V is stronger than the Balmer decrement found in Im galaxies. While it is possible to make the Balmer edge of a galaxy vanishingly small by adding hot stars (OB types), one can only make the edge stronger by adding very cool stars (types later than G). In 130530.6+294608 the drop in flux by a factor of 1.7 is slightly too large to be consistent with the Balmer decrement in stars hotter than G (Bruzual 1981). 130527.1+294634 seems to have a flux decrement of 3. If this were the Balmer edge it would require stars of type K or later to dominate the spectrum. But let us reemphasize that these objects have a nearly flat spectrum from V to K making a SED dominated by such late spectral types impossible. Once again, this argues against the spectral break being the Balmer edge and for the other possibility that the break is the Lyman limit.

An additional source of uncertainty is Lyman-alpha forest absorption which could produce a flux decrement at Lyman-alpha, producing an additional spectral break. From examination of the spectra of $z = 4.0$ quasars, we find that the flux decrement due to the Lyman-alpha forest is about a factor of 2 (Warren *et al.* 1987*a*; Warren *et al.* 1987*b*) and the density of Lyman-alpha forest absorbers scales as $(1 + z)^{2.3 \pm 0.3}$ (Tytler 1987). If we were observing Lyman-alpha forest absorption between B and V, it would correspond to a redshift of 3. Thus we would expect a Lyman-alpha forest amplitude of 1.2 which is much less than is observed. Also, if this were the case we would expect to see a flux decrement further into the blue (3700 Å) which is due to the Lyman limit, but this is not observed in the U band. The optical spectrum of 130527.1+294634 appears to have a flux decrement of a factor of 1.3 ± 0.1 at 5800 Å. This drop is seen in both the FOGS and MMT spectrograph observations and could be due to Lyman-alpha forest absorption ($z = 3.8$) while the larger flux decrement between B and V is due to the Lyman limit (4400 Å). But the significance of this break is questionable and it should be observed at higher signal-to-noise ratios.

We should also comment on the fact that these objects have breaks which are weaker than predicted in traditional PG models (Partridge and Peebles 1967; Meier 1976). Model atmospheres for hot stars (Kurucz 1979) indicate that for $T > 30{,}000$ K the Lyman limit becomes very weak, nearly vanishing at $T > 45{,}000$ K. By adding hot stars, the strength of the Lyman limit can be greatly reduced. In particular Meier's (1976) model had an upper mass cut-off of only 30 $M_\odot$ producing a Lyman limit amplitude of about 10. An upper mass cut off of 100 $M_\odot$ produces a flux decrement between 2 and 4 at the Lyman limit for a constant star formation rate with a Salpeter IMF and solar metallicities (Kennicutt 1988). Lower metallicities, flatter IMFs, and a higher upper mass cut-off all make the break amplitude weaker. The break between B and V in 130527.1+294634 lies nicely in this range but 130530.6+294608 would require a model biased toward hotter stars to accommodate its break amplitude comfortably. Clearly, if an extensive hydrogen nebulae were present, the break amplitudes could increase significantly. A very large ionizing flux, an interstellar medium with a covering factor less than 1, and a disklike geometry would all make escape of a large fraction of the Lyman-continuum radiation possible, suggesting that the Lyman limit need not be large.

Our optical spectrum does not reveal the presence of a Lyman-alpha emission line even though it would be expected in our spectrum from 5000 to 8000 Å if the B to V flux decrement is due to the Lyman limit. The lack of a Lyman-alpha line

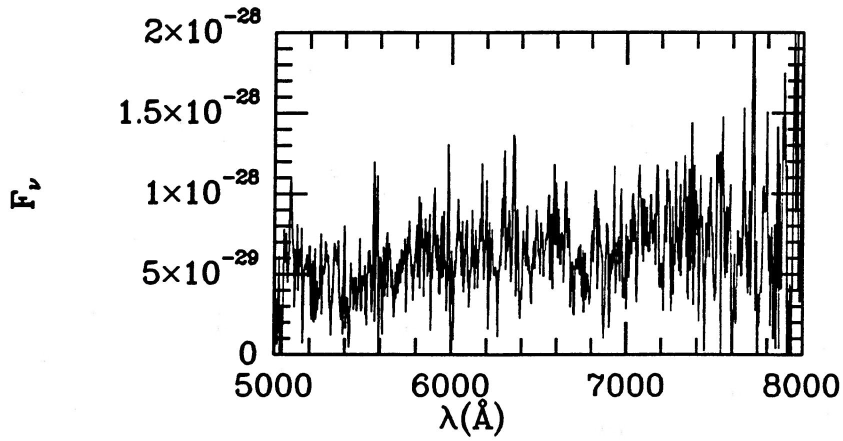

FIG. 6.—Optical spectrum of 130527.1+294634 derived from 5 hours of integration on the MMT. The spectrum possesses only a blue continuum. From the absence of emission lines it appears that the redshift must be greater than 1 to exclude the [O II] 3727 line which is usually present in objects this blue. The only other feature is a slight decrease in flux at 5800 Å which appears in both the FOGS spectrum and the MMT red channel spectrum. This possible break is consistent with being Lyman-alpha forest absorption at $z = 3.8$, while the photometric break between B and V would be the Lyman limit.

with an equivalent width greater than 40 Å is not unexpected in view of the observations of local star formation regions in galaxies by Hartman *et al.* (1988), particularly if the star formation has continued for more than a few times 10^7 yr, the galaxy would already be polluted by metals from massive stars. Since metallicity seems to correlate with weaker Lyman-alpha emission, such galaxies would have weak or nonexistent Lyman-alpha emission (Meier and Terlevich 1981). Also, Lyman-alpha forest absorption could absorb a Lyman-alpha emission line as seen in the blue wings of Lyman-alpha in some high-redshift QSOs.

We can also apply the tests outlined in Paper I to see if these objects are viable PG candidates. The highly uncertain number density of these objects is 1000 per square degree, consistent with PGs having bright phases lasting a few times 10^8 yr at $z = 4$. The brightness of these sources is also consistent with the luminosity of a PG at $z = 4$ with a bright phase of 10^8 yr. The luminosity of $2 \times 10^{30} h^{-2}$ ergs s^{-1} Hz^{-1} ($q_0 = 0$, $h = 0.5$, $z = 4$) would imply a star formation rate of 400 $M_\odot$ yr^{-1}. Making the cosmology small ($q_0 = 0.5$, and $h = 0.8$) would reduce the star formation rate by nearly a factor of 10. Finally, we have a sky brightness of 10^{-25} ergs cm^{-2} s^{-1} Hz^{-1} which is consistent with the sky brightness required to produce the fraction of the metals in current day spheroids or disks.

The optical SED of these objects are similar to objects described by Cowie (1988). He reports that he and Lilly have found objects which have flat spectra between V and I but are faint at B. However, their sources are fainter than 24 in the I band. Since these objects have a spectral break in the optical, we can look for similar objects in the deep CCD photometry of Tyson (1988). We defined a sample of objects bluer than $R-I < 0.5$ and steeper than $B_J - R > 1$. We find a large number of objects in Tyson's data that fit this requirement (7, 21, 46, and 28 in bins centered at $R = 21$, 22.5, 23.5, 24.5). At magnitudes fainter than $R = 24$, Tyson's counts will become incomplete at I for objects this blue. From these, we can compute a more statistically significant sky brightness of $4 \pm 1 \times 10^{-26}$ ergs cm^{-2} s^{-1} Hz^{-1}. This is about one-tenth that expected from spheroids or disks as defined by Cowie (1988). Thus, it does not seem that these objects could be the dominant star-forming phase of spheroids or disks. These could be only the highest redshift members of one of these classes with most of the objects being at lower z and having no strong spectral break in the optical. If these were young disks, for example, this would be expected since disk formation has continued until the current epoch.

We conclude that we have found objects which seem to satisfy all the requirements to be galaxies which are rapidly star forming at $z \approx 4$. For 130527.1+294634 we have argued that the flux decrement between B and V is the Lyman limit on the basis of both the optical spectra and the amplitude of the flux decrement. There also may be a weaker break at 5800 Å which could be consistent with Lyman-alpha forest absorption at $z = 3.8$. The case for 130530.6+294608 is not as strong since we have no optical spectrum for this source and the break amplitude is only slightly too large to be the Balmer decrement in a galaxy with such a flat SED from V to K. The final evidence to verify that these are PGs is a reliable spectroscopic redshift. As can be seen in Figure 6, this may not be easy to achieve since local star-forming galaxies have either very weak or nonexistent emission lines in the UV. A blue spectrum should show the Lyman limit and higher signal-to-noise ratio observations may yet reveal a weak Lyman-alpha emission line or a clear break due to the Lyman-alpha forest. Also, using new IR spectrometers, it may be possible to observe [O II] 3727, Hβ, and [O III] 5007 emission in the near-IR windows. These are clearly the crucial tests of these objects as PG candidates.

ii) *Star-forming Galaxies at $z < 3$*

The remaining blue objects have no large flux decrements in the observed spectral region. Objects similar to these are discussed by Cowie *et al.* (1988) and are presumably star-forming galaxies at $z < 3$, so that the Lyman limit does not pass into the optical. With no spectral breaks and without optical spectra all we can conclude is that the objects have optical SEDs dominated by star formation and that they have redshifts less than 3. The $B-V$ colors of 0.4 are nondescript and are compatible with spiral galaxies with redshifts between 0 and 1.5 (Coleman, Wu, and Weedman 1980). The I photometry of Cowie *et al.* (1988) does point out the star-forming nature of their sources. The typical $V-R$ color of our blue source is 0.3. To compare with the galaxies of Coleman, Wu, and Weedman (1980), our Kron-Cousins R must be converted to Johnson R, a correction of about 0.2 mag ($R_J = R_{KC} - 0.2$). Our $V-R$ color becomes a rather nondescript 0.5 which is compatible with spiral galaxies over a large range of redshifts.

Without redshift information we cannot place very tight limits on the mass contribution of the young population since the objects could be at low redshift. Red galaxies (E, S0, and Sb) typically have $V-K$ colors of 3.2 at zero redshift. The typical limits we and Cowie *et al.* (1988) have are of this order. Without redshift information one needs $V-K$ colors less than 2.2 to conclude that a significant ($M_{\rm young} > 1\% M_{\rm old}$) young population exists. Even if star formation in the past 10^8 yr provided a percent of the stellar mass, this is not incompatible with these objects having constant star formation rates for nearly the Hubble time.

We can also apply the sky brightness test of Cowie (1988) to these sources and we confirm the result of Cowie *et al.* (1988) that they have a sufficient brightness to produce a large fraction of the metals in either disks or spheroids. This type of argument is uncertain by about a factor of 10 because of small number statistics, uncertainty in what fraction of the metal density of the universe is retained in stars, uncertainty in the Hubble constant and the assumption of a perfectly flat SED so that there is no K-correction. It should be very interesting to obtain redshifts so that star formation rates can be determined.

IV. CONCLUDING REMARKS

We have studied two objects previously found in a deep 2 μm survey (Paper I). These objects were selected since they occupied a region of the $R-K$ color-magnitude diagram which should not be occupied by large numbers of galaxies at any redshift. We support the conclusion of Paper I that these objects appear to be a distinct extragalactic population. We find the following:

1. The two objects appear to be isolated luminous galaxies at $z = 0.8$, which are dominated by an old stellar population but with a bluer main-sequence turn-off (near G0) than a current-day elliptical. Also, their SEDs seem to require the presence of an evolving giant branch to explain the red optical–IR colors. The most difficult aspect of the result is that the local density of galaxies this luminous would imply that the probability of finding two such galaxies in 10 arcmin^2 is 1 in 10^4.

2. The presence of these objects suggests a population of very luminous galaxies at $z > 0.7$, with luminosities similar to BCGs at the same epoch but 1000 times more numerous. Because of the small number of objects, it is clearly necessary to make a larger survey to see if these objects are an extreme statistical fluctuation or if some form of strong selective luminosity evolution has occurred by $z = 0.8$.

3. By eliminating these objects as PG candidates we have eliminated models for PGs more luminous than $K = 17.5$. This places some useful constraints on galaxy formation models requiring the initial burst for large elliptical galaxies to be longer than above 10^8 yr.

4. We have confirmed the existence of an object at the tip of the galaxy locus in Paper I with $K = 17.9$ and an $R-K$ color of 6. In view of the two objects described above, it seems likely that it is an additional galaxy like the two described here, at $z = 1.2 \pm 0.2$, making the occurrence of these luminous galaxies even more statistically striking.

We have also looked for objects with blue optical to IR colors, to search for star forming galaxies. We have found two populations of these objects:

1. Two objects have very blue optical to IR colors but have a flux decrement between B and V which is too large to be the Balmer decrement in a star-forming galaxy. An optical spectrum of one source displays only a blue continuum suggesting that $z > 1$. We suggest this source may be a star-forming galaxy at $z = 4$ with the Lyman limit between the B and V bands and a possible break at 5800 Å due to Lyman-alpha forest absorption.

2. Three sources have blue optical to IR colors. The present photometry is not adequate to place a meaningful constraint on how important the young population is without redshift information.

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Note added in proof.—On 1989 February 12 we obtained blue spectra of 130530.6 + 294608 and 130527.1 + 294634 using a 150 l mm^{-1} grating with the "Red Channel" spectrograph on the MMT. The spectra covered the range from 3300 to 8000 Å with 15 Å resolution. A total of four exposures each 1 hr in length were obtained. 130530.6 + 294608 appears to be a blue star-forming galaxy at a redshift of 0.333 with strong [O II] 3727 and [O III] 5007 in emission. 130527.1 + 294634 has a weak emission line at 4727 Å, a strong break at 5050 Å and a weak emission line possibly confused by a strong night sky line at 6350 Å. Based on this spectra we identify these features with [O II] 3727, [O III] 5007, and the 4000 Å break at a redshift of 0.268. This object is very peculiar having both a strong 4000 Å break and a flat blue continuum toward the red of the 4000 Å break.

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