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DEEP 2 MICRON IMAGING OF THE SKY: EVIDENCE FOR A NEW EXTRAGALACTIC POPULATION[1]

R. ELSTON, G. H. RIEKE, AND M. J. RIEKE
Steward Observatory, University of Arizona
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ABSTRACT

We have obtained the first deep images of high Galactic latitude sky at 2 μm. These images reach a 1 σ detection limit of 21.9 mag arcsec^{-2} at K, about 1/20,000 of the sky level. A total of 10 arcmin^2 of the sky was imaged. Of particular interest are two extended objects with K magnitudes of about 17 and $R-K$ colors of about 5. These objects occupy a region of the color-magnitude diagram that is separate from the locus of normal galaxies and should not be occupied by large numbers of normal galaxies at any redshift. We suggest that these may be high-redshift galaxies ($z > 6$) which are in a luminous star-forming phase. Additionally, we have located a group of objects at $K = 18$ which are not detected at R and have $R-K$ colors greater than 5. These may be additional members of the class of objects described above, or they may be weakly evolved elliptical galaxies at $z = 1$–1.5.

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

I. INTRODUCTION

With the recent development of array detectors which operate beyond 1 μm (see Wynn-Williams and Becklin 1987), it has become possible for the first time to investigate the sky to very faint light levels in the near-IR. We report the first deep 2 μm images of high Galactic latitude sky. These images were obtained to search for high-redshift galaxies.

The near-IR is well suited to the study of high-redshift galaxies for several reasons. Even in the rest frame, the spectral energy distributions of normal galaxies peak in the near-IR; the emitted energy is shifted further into the infrared with increasing redshift. High-redshift galaxies are as easily detected at 2 μm as on deep optical CCD images (Walsh *et al.* 1985; Lilly, Longair, and Allington-Smith 1985). In addition, the near-IR holds the promise of being able to detect objects which emit very little radiation in the visual. Such objects could be high-redshift galaxies where the visual lies below the Lyman limit or those which are reddened either by dust within the galaxies or in the intervening space.

Boughn, Saulson, and Uson (1986) used a single-detector near-IR photometer to look at the smoothness of the 2 μm background in a search for primeval galaxies. Although this study did place useful limits, it appeared possible to produce significantly better results with an infrared camera, even on a smaller telescope. This *Letter* describes the technique we developed to use such a camera to obtain infrared images flat to 1/20,000 of the level of the background emission. These images appear to show a class of objects which have a high number density on the sky and very red optical–to–near-IR colors. Their properties are consistent with their being luminous galaxies at extremely high redshift.

II. OBSERVATIONS

We used a 64 × 64 pixel HgCdTe array manufactured by Rockwell International (Rieke, Rieke, and Montgomery 1987). The array was operated at 77 K and provided good response to wavelengths up to 2.5 μm. This array is bonded to a 4 phase CCD which is used as a readout. The readout is linear to 4,000,000 e^-, with a read noise of 600 e^-. The dark current is negligible compared with the background photocurrent when the array is operated at 2 μm. Sufficient photocurrent was accumulated before readouts so that the camera was background-noise–limited.

For this survey we used the Steward Observatory 1.54 m telescope at f/45. Cold reimaging optics in the Dewar gave a plate scale of about 1."2 per pixel. Observations were made on three observing runs during the spring of 1987, and one field was observed during the spring of 1988.

The greatest problem in observing faint objects in the near-IR is the very high background level. The brightness of the background and its nonuniformities varied rapidly enough that it was necessary to observe sky flats every 5–10 minutes or the final image would be degraded. To overcome this problem, we obtained a sky limited image of the field (about 60–80 s of integration) and then wobbled the telescope to an offset field separated from the first by 1′. The image of the field was flattened using the average of the offset field images taken before and after the field observation. Pairs of fields were observed for a total of about 8–10 hr, depending on the night. In all, 100–150 pairs were observed for each of five fields under conditions varying from photometric to light cirrus. It was found that even modest amounts of cirrus greatly degrade the flattening, so these data were eliminated. The 100 or so flattened frames then had their zero levels aligned and were shifted so that objects would register. A median was taken to produce the final image. This image has positive objects from the field and negative objects from the offset field. This doubling of images was found to be acceptable, since the fields were not crowded. The data were photometrically calibrated using standards from Elias *et al.* (1982), and the overall calibration is accurate to about 0.1 mag.

One standard deviation limiting magnitudes of about 21.9 mag arcsec^{-2} were reached on most of the frames. Also, a second version of each image was produced by convolving the image with a 2.5 pixel FWHM Gaussian. The smoothed frames

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

are useful for locating low surface brightness extended objects, reaching a 1 σ limit of 23.4 mag arcsec^{-2}. IRAF[2] APHOT was used to obtain centroid positions and measure magnitudes of the objects in a 12″ diameter aperture as given in Table 1. Positions taken from the IR images and accurate to 2″ are also given in Table 1.

To obtain data for a color-magnitude diagram, we used the Steward Observatory 2.3 m telescope and a TI CCD with a "nearly Mould" R filter. These frames were calibrated using the M67 standards given by Schild (1983). A limiting magnitude of about 24 mag arcsec^{-2} was obtained at R. The positions of objects which were detected at K were examined on the R frame, and photometry in a 12″ aperture was obtained.

Figure 1 (Plate L7) shows the correspondence between objects detected at R and K. The optical frame is shown in gray scale, while the contours are the K intensity. As can be seen from the image, most of the sources detected in the optical are also found in the near-IR frame. We consider this good confirmation that the near-IR imaging technique does produce reliable results. As further confirmation, K photometry for some sources was obtained using the MMT with the liquid helium–cooled InSb photometer. An 8″.7 diameter aperture with a 10″ chopper throw was used. The observations were calibrated using standards from Elias *et al.* (1982). In most cases these observations agreed with the imaging photometry to within the errors.

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

TABLE 1

OBSERVATIONS

R.A.(1950)	Decl.(1950)	K(camera)	K(MMT)[a]	R
084225.03	+444636.9	16.95 ± 0.30	>18.3	22.26 ± 0.30
130528.91	+294504.2	16.76 ± 0.16	17.12 ± 0.15	21.31 ± 0.10
130526.55	+294645.6	16.74 ± 0.10	16.77 ± 0.09	21.91 ± 0.12
130527.98	+294623.9	16.62 ± 0.09	16.62 ± 0.09	21.73 ± 0.13

[a] The MMT aperture photometry includes a uniform correction of −0.24 mag to place it on the same basis as the reduction of the imaging data, which applies to a region of 12″ diameter.

III. DISCUSSION

a) The $R-K$ Color-Magnitude Diagram

Figure 2 presents a color-magnitude diagram for the objects which were detected at K and could have been detected at R. Also on the diagram is a line which represents a passively evolving brightest cluster galaxy with no ongoing star formation, taken from a Bruzual (1983) "c" model normalized to a brightest cluster galaxy ($M_V = -23.3$, $H_0 = 50$, $q_0 = 0$, and $z_f = 5$). This line represents the edge of the region which can be occupied by normal galaxies, since there exist no galaxies which are more luminous or redder than a brightest cluster galaxy. Given the uncertainty in cosmology, this envelope could shift slightly, but the basic idea of a red envelope should persist. Also plotted on the figure is the Bruzual "μ" model with $\mu = 0.5$. This represents a galaxy with ongoing star formation and is thus bluer than the limiting case of no star formation. Because of possible inaccuracies in the near-IR colors of Bruzual models, we have also plotted the expected behavior of

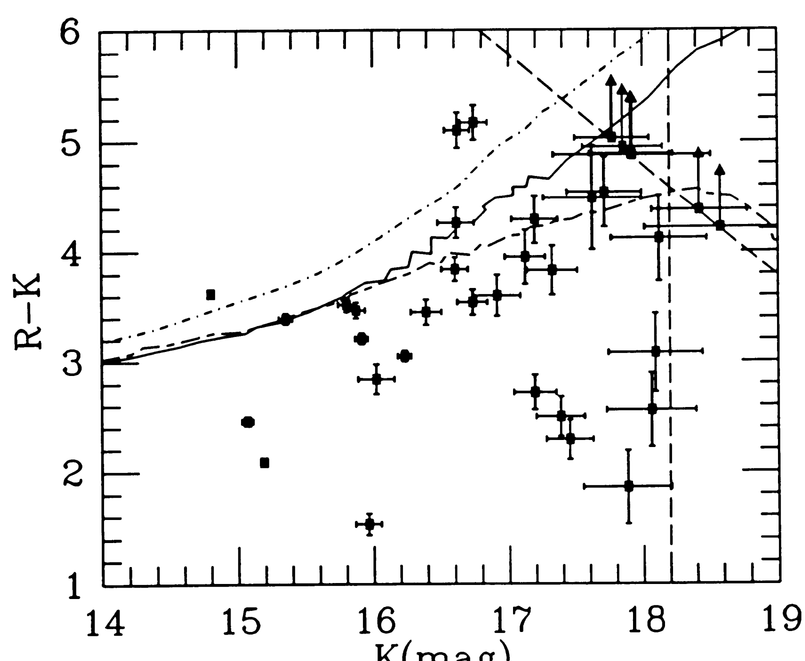

FIG. 2.—$R-K$ vs. K color-magnitude diagram for sources selected at K on 10 arcmin^2 of the sky. The dashed lines indicate the approximate detection limits for galaxies at K and R. The solid line is a passively evolving brightest cluster galaxy, "c" model, taken from Bruzual (1983). The dot-dash line is a nonevolving E galaxy derived from IR observations of nearby ellipticals. This delineates the area of the color-magnitude diagram which can be occupied by normal galaxies. To demonstrate this, a Bruzual $\mu = 0.5$ model with ongoing star formation is shown with the unevenly dashed line. We note that the grouping of galaxies just below the line observationally confirms the notion of a "red envelope." Two objects well separated from the locus of galaxies and above the theoretical "red envelope" are suggested to be a new class of extragalactic objects.

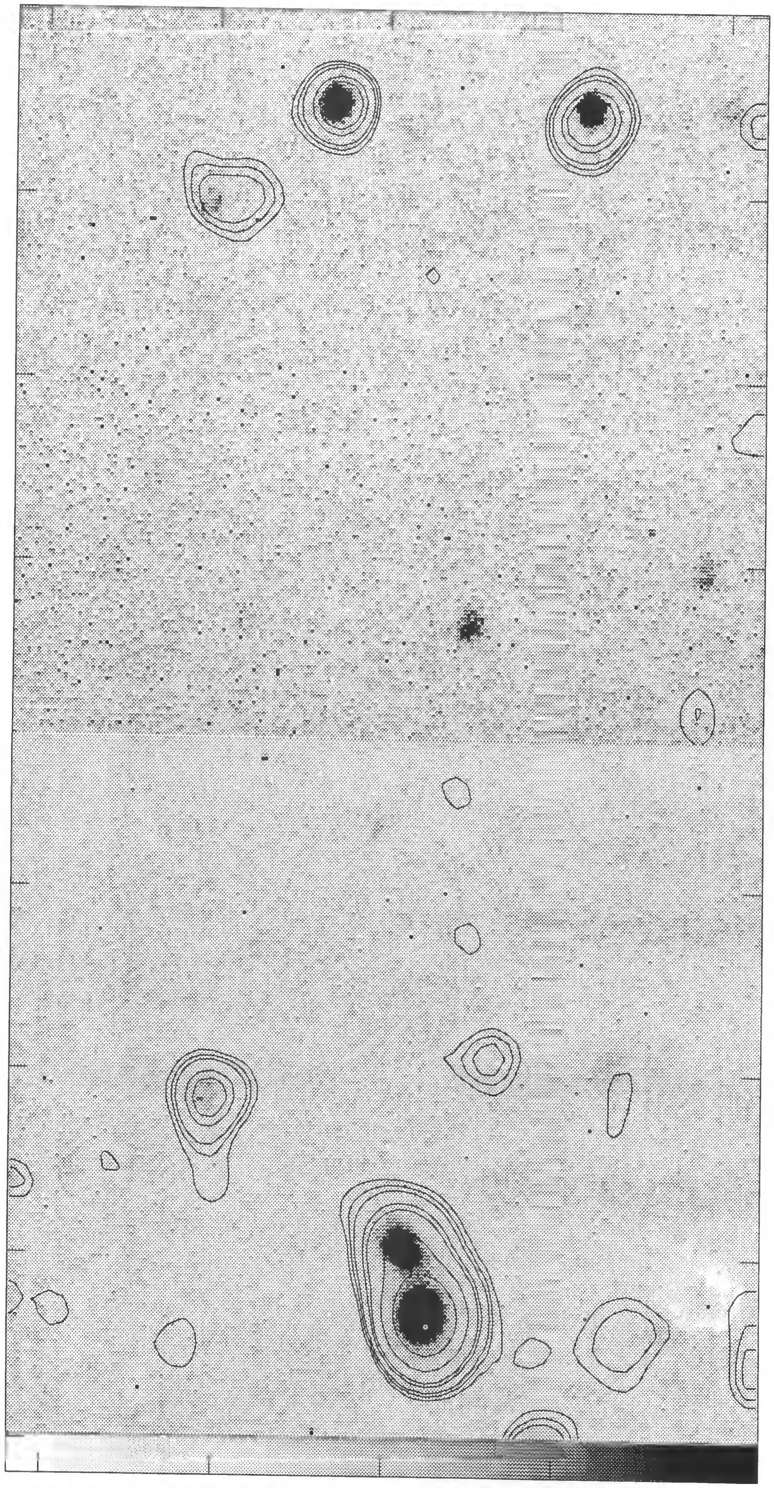

FIG. 1.—Composite R and K image of the field SA57-2. The gray scale represents the R image reaching about 24 mag arcsec^{-2}. The contours are from the K image convolved with a Gaussian, to enhance extended emission. Note the good correspondence between the objects detected at R and K. The northern half of the image is the offset field which was used to flat-field the southern half of the K image. Despite both the northern and southern halves of the K image being recorded on a single image, the crowding of objects is minimal.

ELSTON, RIEKE, AND RIEKE (*see* **331**, L78) a nonevolving brightest cluster galaxy, because this may reproduce the shape of the "red envelope" better than the Bruzual models. This prediction is based on detailed photometry and spectroscopy of nearby elliptical galaxies and spiral bulges. Eisenhardt and Lebofsky (1987) provide confirmation that the colors of high-redshift galaxies always lie on or to the blue side of the no-evolution model prediction.

Most of the objects do lie below the "c" model line. In particular, just below the line there is a ridge of objects which could be red elliptical galaxies at moderate redshift. Thus, even if the reliability of the galaxy models is questionable, this ridge of galaxies can be regarded as the observational locus of galaxies. The $R-K$ colors of model E galaxies, on the red envelope, are monotonic with redshift until $z > 1$ and can be used to derive crude redshift information. From the $R-K$ colors we would expect the galaxies which make up the ridge to have redshifts from $z = 0.4$ to $z = 1$.

In the initial survey, four objects were found to lie outside the region where we have argued that galaxies should be found. These are listed in Table 1. They are extended, have K magnitudes near 17, and have $R-K$ colors of about 5. They are separated and distinct from the ridge of normal galaxies. In the original survey data these objects lay just a few standard deviations from the locus of galaxies and could be outliers from the galaxy distribution. Thus, we obtained confirming observations using the MMT IR photometer. To compare the camera photometry with the MMT observations, a -0.24 mag aperture correction was applied to the MMT photometry assuming a normal curve of growth. As a result of these observations one object (084225.0+444636) was found to be significantly fainter than indicated by the imagery, but three were confirmed (Table 1).

All three of the infrared-selected objects are extended on the IR and R images. Since any common Galactic objects which would have these colors (i.e., halo M dwarfs) are pointlike, they can be excluded; we believe the objects are extragalactic. One of these objects (130528.9+294504) moved near the locus of galaxies on the $R-K$ versus K diagram, as a result of the MMT photometry. It could be a luminous normal galaxy at $z = 0.75 \pm 0.2$, on the basis of its colors. L. L. Cowie and S. J. Lilly (1988, private communication) have obtained a spectrum that suggests a redshift of $z = 0.3$, in which case its colors are very peculiar. A spectrum at higher signal-to-noise ratio is needed to help resolve this dilemma.

The two remaining sources lie outside the zone of normal galaxies in our $R-K$ versus K diagram. The $r-K$ versus K diagram published by Lilly, Longair, and Allington-Smith (1985) suggests they could be similar to the reddest luminous radio galaxies at high redshift ($z = 1$). Photometry of a large sample of 3C galaxies obtained by us in the same photometric system as that of the new objects confirms this conclusion, but only if the two sources are as red as the reddest 15%–20% of the radio sample. From the local luminosity function of Davis and Huchra (1982), it can be shown that roughly 1–2 galaxies per square degree are expected near $z = 1$ and at the luminosity of these two objects. An upper limit to the expected density on the sky can be set from the estimate of Gunn, Hoessel, and Oke (1986) that there should be about 50 galaxy clusters per square degree out to $z = 1$. Even at this upper limit, the probability of finding two such objects in our survey is less than 2%. Allowing for the relatively red colors and for the possibility that the third galaxy is also near $z = 1$, the probability of explaining our observations as a chance detection of normal high-redshift galaxies becomes even less. Alternate explanations might include that we have found some type of heavily reddened galaxy, that our objects are dominated by asymptotic giant branch (AGB) stars from a starburst, or that they are tight clusters of galaxies. From our knowledge of the local galaxy population, none of these explanations is a very attractive way to account for the high density of objects on the sky. In the next section we will discuss the intriguing possibility that they may be galaxies at $z > 6$ undergoing a luminous phase of star formation.

In addition to the two objects which are separated from the galaxies in the color-magnitude diagram, there are also several objects which are not detected at R. These objects are all near $K = 18$ and thus have $R-K$ colors greater than 5. These may be passively evolving elliptical galaxies at $z > 1$, or they could be further members of the class of red objects which are separate from known galaxies. Deeper optical observations will be required to address this point.

b) Could the Reddest Objects Be Primeval Galaxies?

In this section we shall compare the properties of our new class of red objects with those expected for galaxies undergoing a luminous phase of rapid star formation. Because of the very limited observational information and theoretical uncertainties, the purpose of this comparison is not to argue decisively that these objects are primeval galaxies (PGs); rather this comparison is to demonstrate that the properties of these objects are roughly consistent with their being PGs.

The details of PG models differ widely. Partridge and Peebles's (1967) model, which is based on star formation during a dissipationless collapse, predicts an extended object with a bright phase lasting 3×10^7 yr. Meier's (1976) model based on dissipational collapse suggests compact galaxies which are dimmer, with a bright phase lasting about 5×10^8 yr. Baron and White (1987) suggest an inhomogeneous dissipative collapse model where the PG is very extended and the bright phase lasts a few collapse times. Given the diversity of models, we shall use only properties which are common to all the theories to compare with our objects. All the models predict that luminous galaxies produce most of their metals during a bright phase which we shall parameterize in terms of 10^8 yr.

The spectrum of a PG (Partridge and Peebles 1967; Meier 1976) is expected to look like that of a very hot star ($T = 40{,}000$ K). This spectrum is flat from the Lyman limit redward but suffers a large drop from the Lyman limit into the UV. The magnitude of the drop into the UV will depend on the amount of neutral hydrogen surrounding the source. The neutral hydrogen will tend to process the Lyman continuum radiation into hydrogen line radiation. Since we observe a drop by a factor of 20 in F_ν between the K and R bands, this would imply that the Lyman limit lies between these bands ($6 < z < 25$). Meier (1976) predicts the drop in flux to be about 10, and Partridge and Peebles (1967) predict a drop of 18 without hydrogen absorption. Our measured value seems to agree well with that of Partridge and Peebles if there is little hydrogen absorption or with Meier if there is a modest amount of hydrogen absorption.

We can also look at the density of the sources on the sky and compare it with what is expected for PGs. We assume that all luminous E galaxies ($3 \times 10^{-3}\ h^3$ Mpc^{-3}; Davis and Huchra 1982, Ellis 1983) undergo a luminous phase where they generate the bulk of their metals in a dynamical time scale (10^8 yr).

The predicted density of PGs is ($q_0 = 0.5$) (Boughn, Saulson, and Uson 1986)

$$N = 810(N_0/3 \times 10^{-3})(T/10^8)h[(1+z)^{1/2} - 1]^2 \text{ deg}^{-2} .$$

From this it would appear that the density of 1000 per square degree would imply a redshift of $z = 6$ ($h = 0.5$), consistent with the range of z deduced from the $R-K$ color. Since the observed number density on the sky is uncertain and the predicted number density is very sensitive to q_0 and to a lesser extent to T, all we can say is that the density of objects appears consistent with their being PGs.

Finally, we can compare the luminosity of the PG models produced by Meier with the objects we have observed. From Meier's model we can predict the luminosity in the flat part of the spectrum, redward of the Lyman limit:

$$L_\nu = 5 \times 10^{31}(M/10^{12})(T/10^8)^{-1} \text{ ergs s}^{-1} \text{ Hz}^{-1} .$$

For $K = 16.8$ we have $L_\nu = 1.7 \times 10^{32}\ h^{-2}$ ergs s^{-1} Hz^{-1} if we place the object at $z = 7$ ($q_0 = 0$). Once again this is a rather uncertain calculation, given the uncertainties in q_0, z, T, or M. For the Partridge and Peebles value of T we obtain a value of L which is consistent with that observed. These luminosities imply a very large star formation rate $10^4\ M_\odot$ yr^{-1} to produce $10^{12}\ M_\odot$ of stars in 10^8 yr. A bimodal initial mass function as proposed by Larson (1986) could reduce this mass requirement greatly.

The sky brightness can be related to the total amounts of metal produced in a manner which is independent of cosmology. We shall follow Cowie (1988) and relate the K sky brightness to the current metal density of bulges and elliptical galaxies. Cowie (1988) gives

$$S_\nu = 4 \times 10^{-25}(\rho_z/2 \times 10^{-34} \text{ g cm}^{-3}) \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ Hz}^{-1} \text{ deg}^{-2} .$$

From the brightness and observed density of our objects we find S_ν of about 10^{-24} ergs cm^{-2} s^{-1} Hz^{-1} deg^{-2} with an uncertainty of at least a factor of 2 or 3. Cowie (1988) suggests a current metal density (ρ_z) in galactic bulges of $2 \times 10^{-34}\ h^2$ g cm^{-3}, but he notes that this could be higher by a factor of 2 or 3. Within the uncertainties it does seem that our objects are consistent with the current metal density in bulges.

IV. CONCLUDING REMARKS

We obtained deep near-IR imaging to study extragalactic populations. In this preliminary investigation we have used a color-magnitude diagram to identify both normal galaxies with $z = 0.3$–1 and what appears to be a new distinct population. We have shown that the new population has properties roughly similar to what would be expected for large galaxies at $z > 6$ undergoing a rapid luminous phase of star formation, and we suggest that these are good candidates to be primeval galaxies. Alternative interpretations include the possibility that they are heavily reddened or that they have very large AGB populations. A test of the identification of these objects with a population of primeval galaxies can be made with complete optical to near-IR spectral energy distributions (SEDs).

The normal galaxies identified are also of importance for studies of galaxy evolution, since they are found in the near-IR, which is only weakly affected by evolution of the stellar populations. Optically selected groups of galaxies may be biased toward finding objects with increased UV emission and thus stronger evolution. An extended survey would produce enough galaxies to be used for studies of galaxy evolution and cosmology based on field galaxies. It will also be interesting to test whether the $R-K$ color does provide a reliable redshift indicator of the passively evolving galaxies.

The objects which are not detected at R are of great interest. They may be further members of the class of objects with properties which are consistent with those of PGs. Alternatively, they may be luminous galaxies which have had only passive evolution of their stellar populations to $z > 1$. If they were passive galaxies, they would imply an old formation epoch. Obtaining optical frames to $R = 26$ should resolve this issue.

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R. ELSTON, G. RIEKE, and M. RIEKE: Steward Observatory, University of Arizona, Tucson, AZ 85721