Near Infrared Observations of a Redshift 5.34 Galaxy: Further Evidence for Significant Dust Absorption in the Early Universe[1]

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ABSTRACT

Imaging at 1.25 and 2.20μm has been obtained of the field containing the galaxy (RD1) found at redshift $z = 5.34$ by Dey, et al.(1998). This galaxy has been detected at 1.25μm, while the lower redshift ($z = 4.02$) galaxy also found in the same field by Dey, et al. was detected at both 1.2 and 2.2μm. The colors of both of these galaxies are suggestive of significant reddening of a young stellar population. Combined with photometric observations of other high redshift systems, this shows that dust is an important component of young galaxies even at redshifts in excess of 5. The extinction corrected, monochromatic luminosity of RD1 at 1500Å is 1-2 magnitudes greater than a typical star forming galaxy at $z \sim 3$.

Subject headings: Galaxies: High Redshift; young

1. Introduction

In the last several years, the combination of new wavelength dropout discovery techniques (e.g. Steidel et al. 1996) coupled with the incredible power of deep imaging of the Hubble Space Telescope and the spectroscopic capabilities of a new generation of large ground-based telescopes, has lead to an astonishing blossoming of the study of galaxies at redshifts of $z = 2 - 4$, when the Universe was less than 10-20% of its current age. A recent breakthrough in this field has been the discovery of a galaxy at a redshift of $z = 5.34$ by Dey et al. (1998). Besides being the highest redshift object presently known, this galaxy is important because it is apparently neither gravitationally lensed, nor the host of a powerful active nucleus. Thus there is hope that detailed studies of this system and others like it at $z \sim 5$ will shed light on the intrinsic, stellar properties of very young galaxies. Because visible observations of objects at such high redshifts are sampling the restframe ultraviolet part of the spectrum, they are very sensitive to the presence of small amounts of intervening dust. Dust is important at these redshifts for three simple reasons. First, intrinsic luminosities and star formation rates are always underestimated when dust is not taken into account. This may have vast implications for metal production at early epochs (Madau et al. 1996, Meurer et al. 1997). Second, dust may hide entire populations of high redshift, star-forming galaxies from detection because of sample selection effects (e.g. Dey, Spinrad & Dickinson 1995). Third, dusty interstellar media in galaxies at $z > 3 - 4$, by their very nature, imply previous episodes of star formation and enrichment, pushing the first epoch of star formation to even higher redshifts. Although "pollution" of the ISM can happen relatively quickly from a "primordial" state (e.g. Matteucci & Padovani 1993), dusty systems at high redshift always provide a lower limit to the redshift of the earliest star formation. Since there is mounting evidence for dust (in emission and via absorption) in high redshift galaxies (e.g. Dunlop et al. 1994, van Ojik et al. 1994, Ivison 1995, Dey, Spinrad & Dickinson 1995, Armus et al. 1998) it is natural to ask whether dust is present in galaxies at $z > 5$.

To understand the true nature of the $z = 5.34$ galaxy discovered by Dey, et al. (1998), hereafter referred to as RD1 - for Red Dropout 1, it is necessary to know whether it is being viewed through a significant amount of dust. To achieve this it is essential that such object be observed at the longest possible wavelengths. We report in this paper serendipitous observations made of this galaxy at J (1.25μm) and K (2.20 μm). The galaxy is clearly detected at J, and simple fits to the observed optical-infrared colors suggest a reddened, young stellar population. In the discussion we adopt the cosmological parameters $H_0 = 50$ km s^{-1} Mpc^{-1} and $q_0 = 0.5$. Throughout this paper we refer to broad-band magnitudes measured with respect to Vega, such that J= 0 mag and K= 0 mag correspond to 1578 Jy and 646 Jy, respectively.

2. Observations and Data Reduction

As part of an observational study of high redshift radio galaxies (e.g. Armus, et al. 1998) we observed the most distant known radio galaxy, 6C0140+32 in August 1997 and January 1998 using the near infrared camera (NIRC) on the K1 telescope of the W.M. Keck Observatory (Armus, et al. 1998b). The instrument is described in detail by Matthews and Soifer (1994). It has a 256×256 InSb array with $0.15'' \times 0.15''$ pixels for a $38'' \times 38''$ field of view. On 18 August 1997, the field was observed at K under conditions of thin cirrus and good seeing ($\sim 0.5''$). On January 16, 1998 we observed this field under clear, photometric conditions at J and K in excellent seeing ($0.4 - 0.5''$ FWHM). On 17 Jan 98 we also observed the field at K under conditions of good seeing with thin cirrus.

The target for the observations was centered in the field of view, and observations were made with individual integration times of 60 seconds. In the August observations the target was moved in a regular 9 point square grid covering a size 10″ on a side, with the center of the grid moved by $1 - 2''$ between grids. In the January observations, the target was moved randomly over an area of 10″× 10″ between individual observations in order to affect optimal sky subtraction.

Because the galaxy RD1 and the companion galaxy BD3 (for Blue Dropout 3) at a redshift $z = 4.022$ were only $\sim 12''$ from the targeted object, they were contained in virtually every frame, and the combined data achieved the full sensitivity of the observation at the location of RD1 and BD3 at each wavelength.

A bright star in the center of the NIRC field was used to accurately register the successive frames for coaddition. To remove time-variable fluctuations in illumination, separate sky and normalized flat-field frames were created from the data for each three images, by taking the median of the nearest 7-9 frames. After being trimmed to a size of 251 × 251 pixels, the individual data frame are sky subtracted and flat fielded and are shifted to a common dc level after known bad pixels are flagged. These processed images are then aligned, using integer pixel shifts, and combined using a clipped mean algorithm. The FWHM of a point source in the final mosaic, as determined from several stellar images in the field, was approximately 0.5″ at J and 0.45″ at K. The photometry was based soley on the data from 16 Jan 98, when conditions were photometric. The data were calibrated by reference to the infrared standard stars of Persson (1997).

3. Results

The J and K images of the field centered on RD1 are shown in Figure 1. The J data are from 16 Jan 98 only, while the K data are from 18 Aug 97, 16 Jan and 17 Jan 98. We obtained a total of 70 minutes and 92 min of integration at J and K, respectively.

In order to bring out the faint, high redshift sources RD1 and BD3, the data in Figure 1 have been convolved with a circular gaussian having a FWHM equal to the measured stellar FWHM in the final J and K-band mosaics. In this figure, a 12″ section of the mosaics are displayed. Objects RD1 and BD3 are both detected in the J-band image. At K, BD3 is marginally detected, while RD1 is undetected. The J-band image of RD1 is resolved in the NS direction, while that of BD3 is unresolved.

Because the objects RD1 and BD 3 are separated by $\sim 1.2''$ obtaining photometry of both systems required special care. A square beam, 0.75″ on a side, was centered on both RD1 and BD3. The sky was taken to be adjacent and to the south for RD1, and adjacent and to the north for BD3. As a check on this small beam photometry, aperture photometry was obtained of the combined flux from both objects, and this total was distributed between the two objects based on the one dimensional distribution of flux along the line between the two sources. The two methods agreed well, and the magnitudes are reported in Table 1. In this table we have also included the I-band magnitudes of these objects as reported by Dey et al. (1998).

To use the broadband magnitudes to derive continuum fluxes requires correction for contamination by strong emission lines contained within the filter bandpasses. In the case of RD1 the J filter contains redshifted CIII] 1909Å (at 1.206μm), while the K filter contains redshifted [OII]3727Å (at 2.355μm). Heckman et al (1998) have recently compiled a composite UV spectrum of nearby starburst galaxies that shows the CIII] emission-line equivalent width to be generally less than 10Å. This is small compared to the uncertainty in the measured J-band magnitude of RD1. Similarly, the average radio galaxy spectrum in McCarthy (1993) can be used as an upper limit on the strength of CIII] in RD1. If the equivalent width of CIII] in RD1 is the same as in a typical radio galaxy (32Å), the CIII] line would contribute only about 8% of the total flux in the J filter. Thus we conclude that the correction for line emission in the J-band for RD1 is not significant. However, unlike CIII], the [OII] 3727Å line can be quite strong in star forming galaxies, having rest-frame equivalent widths of 50 – 100 Å (e.g. Cowie et al. 1995, Gallagher et al. 1989). At an equivalent width of 100Å [OII] would contribute 14% of the (3σ) limit we measure for the K-band flux from RD1.

In the case of BD3, there are no strong lines expected to be present in the J filter, unless MgII at 2800Å has a broad, blue wing, which is unlikely for a starburst galaxy. The only emission feature that could contribute to the K-band measurement is the Hβ line. While potentially strong, the redshifted wavelength of Hβ (2.44μm) places it at the very edge of the K filter and it should have a negligible effect on the total flux.

4. Discussion

The most important result of the present observations is simply that the galaxy RD 1 was detected at J. This immediately implies that it is a much redder system than expected for any dust free, young galaxy model. The expected color of an unreddened, star forming galaxy with f_ν ~const is I−J~ 0.5 mag and I−K~ 1.5 mag, while the apparent color of RD1 is I−J= 2.2 ± 0.3 mag and I−K < 3.5 mag.

The "blue dropout" source BD3 is also redder than expected for an unreddened starforming galaxy, having I−J= 1.2 ± 0.3 mag and I−K= 2.2 ± 0.5 mag, and is likely to also contain significant amounts of dust. For comparison, the colors of the galaxy CL1358+62G1 at a redshift of $z = 4.92$ (Franx et al. 1997, Soifer et al. 1998) are I−J= 1.2 ± 0.1 mag and I−K= 2.1 ± 0.2 mag. For CL1358+62G1, Soifer et al. have shown that galaxy models with reddenings of $0.1 <$ E(B−V) < 0.4 mag provide substantially better fits to the overall energy distribution than do models with no reddening. We find the same is true for both

RD1 and BD3 (see below).

With only an I−J color, and a limit on the I−K color, it is difficult to disentangle the effects of intrinsic galaxy color and reddening. However, we can identify a range of allowable ages and reddening values for a set of simple galaxy models. We begin by using the aging, instantaneous burst models of Leitherer and Heckman (1995) for metal abundances of $Z_\odot$ and $0.1Z_\odot$, and compare the predicted UV continuum slope between 1200Å and 1900Å to the slope measured between the I and J filter measurements of RD1 (rest frame wavelengths of 1278Å and 2000Å, respectively) and attribute the discrepancy to reddening. The results are given in Table 2.

From Table 2, it is apparent that the reddening we derive depends on both the age and metal abundance of the galaxy. Young galaxies require significant line of sight reddening to match the observed color. Older galaxies (up to $\sim 3 \times 10^8$ yrs old) can accomodate the observed color without reddening, however these dust-free models provide significantly worse fits to the data (see below). As expected, the required reddening, at a given age, is larger for systems with lower metal abundances.

A more refined estimate of how well galaxy models fit to the observational data can be obtained by using the synthetic spectral energy distributions of Bruzual and Charlot (1993, 1996). Because we are simply trying to set the constraints on reddening and stellar age, we again chose to fit aging, instantaneous starburst models, since these are the reddest galaxies at a given age, and thus they require the least amount of dust reddening to match a given observed spectrum. Continuous star formation models will always require more reddening by dust.

The comparison of the present data with the galaxy models shows that for both RD1 and BD3, young, dusty models, provide better fits than do older models with no reddening. In the case of RD1, the best fit to the data by a galaxy model having no dust requires an age of ∼0.5 Gyr. At a redshift of $z = 5.34$, this implies a minimum formation redshift of z ∼7.5. However, the dust-free model produces a significantly worse fit to the data than does a model where the age of the system is much younger ($< 10^8$ yrs), but which includes reddening by dust in amounts in excess of $A_V > 0.5$ mag.

If RD1 is indeed a reddened, young galaxy then its luminosity and star formation rate are both higher than those estimated by Dey et al.(1998). If RD1 has an age of less than 10^8 yr and a metal abundance $\sim 0.1 Z_\odot$, the rest-frame UV reddening is larger than 1.3 mag, and the extinction at 1270Å is a minimum of $3 - 3.6$ magnitudes, depending on whether the reddening curve for the SMC (Gordon and Clayton 1998) or that determined from starburst galaxies by Calzetti, et al. (1994) is adopted. The lower value is based on the SMC reddening law. Assuming the reddening to the Lyα line is the same as that to the far UV continuum, the Lyα and UV continuum luminosity are larger by factors of $15 - 30$ than those determined by Dey et al. (1998) for no reddeing. The extinction-corrected star formation rate in RD1 is then $90 - 180 h_{50}^{-2} M_\odot \mathrm{yr}^{-1}$, and the monochromatic luminosity at 1500Å is $1 - 2$ magnitudes larger than L^*_{1500} determined by Dickinson (1998) for $z \sim 3$ starburst galaxies.

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Table 1: Photometry of RD1 and BD3

Object	I	J	K
	mag	mag	mag
RD1	26.5±0.1	[a,b]24.3±0.3	23.1[c]
BD3	25.1±0.1	[a] 24.1±0.3	23.0±0.4

[a]from Dey et al. (1998) as measured in a 1.5″ diameter circular beam

[b]corrected for Lyα emission in the bandpass (Dey et al. 1988)

[c] 3 sigma limit, corresponding to a 1 sigma limit of 24.3 mag

Table 2: Reddening vs. Starburst Age for Galaxy RD1

Metal Abundance	T< $10^{6.5}$ yr	10^{7} yr	$10^{7.5}$ yr	10^{8} yr	$10^{8.5}$ yr
$Z_{\odot}$	1.97 mag	1.72 mag	1.36 mag	0.75 mag	0.0 mag
$0.1Z_{\odot}$	1.97 mag	1.72 mag	1.53 mag	1.23 mag	0.5 mag

Reddening, in magnitudes, between 1278Å and 2000Å in the rest frame of RD1 based upon the measured I and J-band flux densities, and the instantaneous starburst models of Leitherer & Heckman (1995). To convert these values to E(B−V), a reddening curve must be adopted. From the recently determined SMC reddening curve (Gordon and Clayton, 1998) corresponding approximately to $0.1Z_{\odot}$, E(B−V)$\sim$0.14E(1280Å −2000Å), while from the UV reddening curve derived for starburst galaxies by Calzetti, et al. (1994), E(B−V)$\sim$ 0.85E(1280Å −2000Å)

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Figure Captions

Fig. 1.— Images of the field of 6C0140+32 RD1 at J and K obtained with the W.M. Keck Telescope. The scale and orientation of each field is shown. The images show the locations of the objects RD1 (z =5.34) and BD3 (z =4.02) identified by Dey, et al. (1998). After coadding the data in each filter, the images have been smoothed with a gaussian matching the average FWHM of a stellar source in the final mosaic (see text for details).

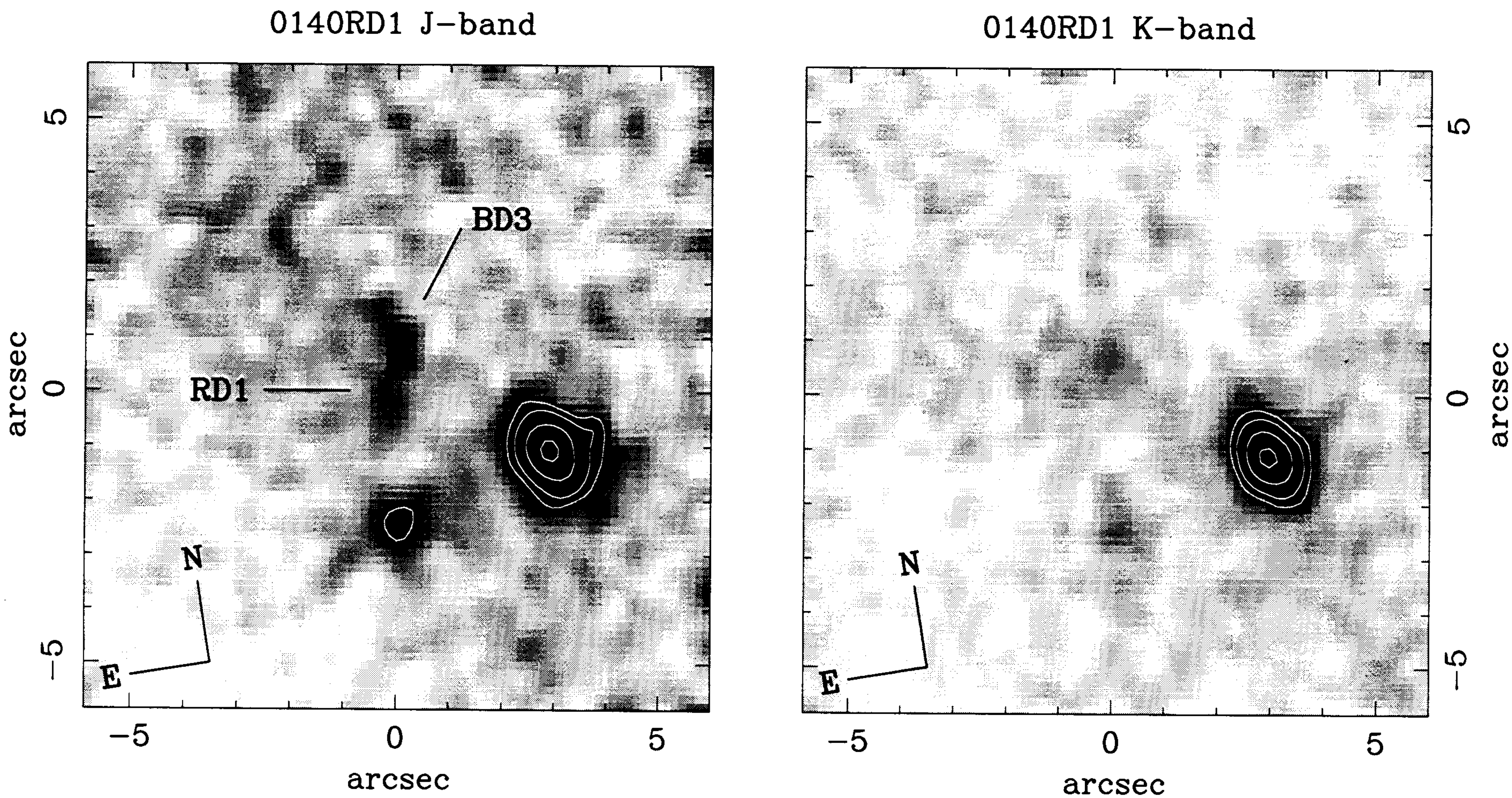

Fig. 1