AN INFRARED EMISSION-LINE GALAXY AT Z = 2.43

S. V. W. BECKWITH
Max-Planck-Institut für Astronomie, Heidelberg, Germany; svwb@mpia-hd.mpg.de

D. THOMPSON
Max-Planck-Institut für Astronomie, Heidelberg, Germany; djt@mpia-hd.mpg.de

F. MANNUCCI
Centro per l'Astronomia Infrarossa e lo Studio del Mezzo Interstellare, CNR, Florence, Italy; filippo@arcetri.astro.it

AND

S. G. DJORGOVSKI
California Institute of Technology, Pasadena, CA 91125; george@oracle.caltech.edu

Received 1997 November 14; accepted 1998 April 8

ABSTRACT

An object discovered during an infrared survey of the field near the quasar B2 0149+33 has an emission line at 2.25 μm that we interpret as Hα at a redshift of 2.43. The K-band image shows two compact components 10 kpc apart, surrounded by more extended emission over ~20 kpc. The Hα emission appears to be extended over ~15 kpc (2") in a coarsely sampled (0.8 pixel⁻¹) image. The star formation rate may be as high as 250–1000 M_☉ yr⁻¹, depending on the extinction. Alternatively, the line may be powered by an active nucleus, although the probability of serendipitously discovering an AGN in the survey volume is only ~0.02. The increasing number of similar objects reported in the literature indicate that they may be an important, unstudied population in the high-redshift universe.

Subject headings: galaxies: distances and redshifts — galaxies: individual (cK39)

1. INTRODUCTION

Discovering the properties of galaxies at redshifts greater than 1 requires techniques that can readily distinguish the high-redshift objects from those at lower redshift that predominate in any deep image. Multiwavelength approaches are especially fruitful and have been dominated to date by optical and radio surveys. The use of photometric redshifts based on the strong Lyman break redshifted into the optical band has been one of the most successful of these techniques (Steidel et al. 1996 and references therein). Methods using infrared images are beginning to uncover objects not easily discovered with optical or radio methods that may, nevertheless, constitute a significant fraction of the high-redshift population. These include objects distinguished by unusually red colors (Elston, Rieke, & Rieke 1988; Soifer et al. 1994; Graham et al. 1994; Hu & Ridgway 1994; Cowie et al. 1994; Dey, Spinrad, & Dickinson 1995) and objects with emission lines redshifted to infrared wavelengths (Songaila et al. 1994; Thompson, Mannucci, & Beckwith 1996, hereafter TMB96; Malkan, Teplitz, & McLean 1995; Bechtold et al. 1997). These objects have been interpreted as elliptical galaxies (Graham et al. 1994; Hu & Ridgway 1994; Dunlop et al. 1996), young protogalaxies undergoing bursts of star formation (Eisenhardt & Dickinson 1992; Graham & Dey 1996; Malkan, Teplitz, & McLean 1996; Yee et al. 1996; Bechtold et al. 1997), or active galactic nuclei (Cowie et al. 1994; Dey, Spinrad, & Dickinson 1995). All of these populations could be significant for cosmology, since the first case implies massive galaxy formation at redshifts greater than ~3, the second indicates a substantial population of young galaxies that can be discovered only in infrared surveys, and the third implies a population of infrared-bright active galactic nuclei (AGNs) comparable in number density to the populations of AGNs discovered by more traditional methods. Only a few such objects have been studied in enough detail to reveal redshifts, source morphologies, and colors.

In the course of our survey for emission-line galaxies (TMB96), an object was discovered near the quasar B2 0149+33 with an emission line at 2.25 μm, the same wavelength as the quasar's Hα line at a redshift of 2.43; we call this object TMB 0149–cK39, or simply cK39. A spectrum between 1.5 and 2.4 μm, presented and discussed here, confirmed the presence of an emission line nearly coincident in wavelength with that of the quasar. The object is very red, making it unusual among known distant galaxies. This paper describes the results of these observations and suggests that such objects may be common, but previously unobservable owing to the lack of optical emission.

2. OBSERVATIONS

The object was discovered in the course of a survey that covered 250 square minutes of arc at wavelengths where the Hα line would appear at redshifts between about 2.1 and 2.7 (TMB96). The total comoving volume was 3 × 10⁴ h₅₀⁻² Mpc⁻³ (h₅₀ = H₀/50 km s⁻¹ Mpc⁻¹, q₀ = 0.5 are assumed throughout this paper). Within this volume, there was only one candidate discovered by comparing images in broad- and narrowband filters, searching for emission-line objects that were brighter in the narrowband image and more than 3σ above the background. Simultaneous spectra in the H and K bands of the candidate and the quasar, B2 0149+33, were taken with the grating spectrometer CGS4 at the UKIRT telescope on the nights of UT 1996 January 12 to 14. The weather was not photometric, with variable seeing...
at \( \sim 2.5 \), measured from the quasar continuum. The objects were dithered along the slit by 10' to 20', and the spectra at these two positions was subtracted to eliminate sky emission. The 2 pixel wide slit (2.4) produced a spectral resolution of 195\( \lambda \) (\( \mu \)m), or 438 at the position of the quasar's H\( \alpha \) emission line. The spectra of the quasar and cK39 were extracted using variance weighting in the IRAF apextract package, summing across a 2 pixel wide window along the slit. The poor and variable seeing, combined with uncertainties in the positioning of the slit, preclude an accurate measurement of the line flux from this spectrum.

Figure 1 shows the resulting spectra, centered on the H\( \alpha \) line of the quasar. The quasar spectrum shows a strong H\( \alpha \) line redshifted to 2.25 \( \mu \)m, while a faint emission line at the same wavelength is apparent at the position of cK39. The bottom part of the figure shows the extracted spectrum of the line in cK39 at full resolution, overlaid with a scaled plot of the quasar's H\( \alpha \) line. The formal signal-to-noise ratio of the emission line is 6.3, inadequate to conclude more than that an emission line is present, and it is impossible to separate the line into individual components, for example, from H\( \alpha \) and [N II]. Although the emission line in cK39 appears somewhat broad, with a formal line width of 2200 km s\(^{-1}\) (FWHM), it may be unresolved within the considerable uncertainties. The line could thus arise from a Galactic object with essentially zero width or an active nucleus with broad lines.

Figure 2 shows images taken on the nights of UT 1997 September 9 (K band) and UT 1997 October 3 (R band) with the 10 m W. M. Keck telescopes, obtained in order to determine the morphology of cK39 more accurately. The K-band image shows that cK39 is a pair of extended sources 1.3 apart, cK39E and cK39W. The western component, cK39W, has \( K = 20.27 \pm 0.06 \) in a 0.5 radius aperture; the eastern component has a lower surface brightness, with \( K = 20.57 \pm 0.07 \) in the same aperture. Each component is more extended than the 0.6 seeing profile; cK39W is 0.75 and cK39E is 0.9 (FWHM), uncorrected for the seeing. The continuum-corrected line emission did appear to be extended in the original survey images, although it is
difficult to make an unambiguous determination of the extent in the coarsely sampled survey data. We were, however, unable to reproduce the distribution of light in cK39 using one or two point sources scaled down from a much brighter star in the same image. The extended morphology suggests that the object is a pair of galaxies, perhaps caught in the process of merging. The candidate cK39 is barely detected in the R-band image (0".6 seeing) as a low surface brightness diffuse object. It is clearly extended along an east-west line, but the two components cannot be readily distinguished in the image for the purposes of photometry. The center of light is close to cK39W, however, indicating that the western component is brighter and bluer than cK39E.

Table 1 lists the parameters of the various observations along with the results, including those from TMB96 where relevant. The magnitudes of the individual components were derived using 1" apertures, and they do not include extended light that contributes to the total magnitude. The line fluxes were derived from a comparison of the original narrow- and broadband images with 0".8 pixel resolution. The systematic uncertainties of deriving photometric magnitudes between the narrow- and broadband filters, combined with the problem that the center of the narrowband filter is at one edge of the broadband filter, requiring uncertain color corrections, means that the tabulated line flux may be 50% brighter or fainter (1σ) than the listed value.

3. DISCUSSION

The coincidence of line emission between the quasar and cK39 and the ~2" size of cK39 suggest that the line is Hα + [N II], and that cK39 is at a redshift of 2.43. If the object were in the Galaxy or at very low redshift, the only plausible identification would be the v = 2–1S(1) line of H2 at 2.248 μm, a weak line always accompanied by a series of other lines (e.g., Shull & Beckwith 1982) that are not seen in our spectrum. The other strong lines from extragalactic objects that are likely to appear at these wavelengths are Brγ (λ0 = 2.1656 μm), Pα (λ0 = 1.8751 μm), and [Fe II] (λ0 = 1.6435 μm). If the line were Brγ at z = 0.039, the Pα line would be seen at 1.948 μm, within the range of our spectrum and strong enough to show up even through the poor telluric transmission. The shock-excited line [Fe II] (at z = 0.369) can be strong in merging systems (Elston & Maloney 1990; Lester, Harvey, & Carr 1988), as suggested by the morphology of cK39 in the K band, although Paβ would be visible in our spectrum at 1.755 μm. Pα is thus the only reasonable alternative to Hα + [N II] that could explain the spectrum of cK39. For the [Fe II] interpretation, however, one would also have to consider that the cK39 system would then be very low luminosity, several magnitudes fainter than an L* galaxy.

Table 2 gives some of the properties of the object, assuming that the line is either Paα or Hα. The star formation rates have been estimated using Kennicutt’s (1983) empirical relationship between Hz line luminosity and star formation rate (SFR), assuming zero extinction and no contribution from an active nucleus. We ignore the possible contribution of [N II] to the Hα line flux, following the arguments of Bechtold et al. (1997), which also apply to cK39 for the purposes of this calculation. Table 2 includes estimates of the visual extinction, A_V, local to cK39 needed to produce the observed R – K = 5.5 from various template galaxy spectra (Bruzual & Charlot 1993; Coleman, Wu, & Weedman 1980). Galactic extinction at the latitude of cK39, −27°:3, is estimated to be 0″:3 at R and 0″:1 at K (or K′), which is negligible considering other uncertainties. An extinction of A_V ~ 1.7 (midrange for different galaxy models) is required to redder a young starburst galaxy to produce the observed color at a redshift of 2.4, while an extinction of A_V > 4 would be required to produce the observed colors if cK39 is at the lower redshift.

Other possible lines exist, but they are invariably weaker than the hydrogen lines
Table 2 also lists the minimum and maximum volume densities of objects within the $\pm 2 \sigma$ probability band at different redshifts, computed by setting the Poisson probability to 0.046 (2 $\sigma$). If the line is $H\alpha + [N\, ii]$, the probability might be substantially enhanced if objects exhibit even mild clustering with quasars. The maximum separation between cK39 and the quasar is 9 Mpc, adopting the 1 $\sigma$ maximum redshift difference of 0.01 allowed by the spectra ($\Delta z = 0.002 \pm 0.0045 \mu m$ for $\lambda_0 = 0.656 \mu m$). The minimum projected separation is 390 kpc. In this case, the average density of such objects might be lower by a factor of 10 or more than $\rho_{\text{min}}$ without affecting the probability estimates. Our survey covered a much larger volume near redshift 2.4 than at redshifts below 1, and the global star formation rate appears to be larger at $z \sim 2.4$ than at $z \sim 0.2$ (Madau et al. 1996). The chance of discovering any kind of exotic object should thus be greater at higher redshifts. We therefore believe that this line is $H\alpha + [N\, ii]$.

The object cK39 shares some properties with other infrared-bright galaxies at high redshift: MS 1512–cB58 (Yee et al. 1996; Bechtold et al. 1997), MTM 095355+545428 (Malkan et al. 1995, 1996), Hawaii 167 (Cowie et al. 1994, now known to be a quasar), and HR 10 (Graham & Dey 1996). Characteristics of these objects are compared in Table 3. All have large apparent star formation rates compared to the 5–100 $M_\odot$ yr$^{-1}$ typical of young galaxies in the redshift range 1–3 found in dropout samples (Steidel et al. 1996; Pettini et al. 1997; Dickinson 1998). If cK39 is a galaxy or ongoing merger-induced starburst, powered solely by photoionization from massive stars, it has one of the highest star formation rates seen in high-redshift objects.

Graham & Dey (1996) had difficulty reconciling properties of HR 10 that are nearly identical to cK39. HR 10 was discovered because of its color and only later discovered to have a strong emission line; the opposite is true for cK39.

### Table 1

| Property                      | B2 0149+33 | cK39E | cK39W |
|-------------------------------|------------|-------|-------|
| R.A. (2000)                   | 1 52 34.52 | 1 52 30.93 | 1 52 30.83 |
| Decl. (2000)                  | + 33 50 33.9 | + 33 50 55.3 | + 33 50 55.3 |
| Size (arcsec)                 | ... | 0.9 | 0.75 |
| $K$ magnitude (1" aperture)   | ... | 20.57 ± 0.07 | 20.27 ± 0.06 |
| $K$ magnitude (4" aperture)   | $K' = 15.8$ | 18.87 ± 0.07 | 18.87 ± 0.07 |
| $R$ magnitude (4" aperture)   | ... | 23.45 ± 0.10 | 23.45 ± 0.10 |
| $I_{\text{max}}$              | 2.250 ± 0.002 | 2.248 ± 0.004 | 2.248 ± 0.004 |
| $F_{\text{R}}$ (ergs s$^{-1}$ cm$^{-2}$) | $8.4 \times 10^{-15}$ | $6.5 \times 10^{-14}(\pm 50\%)$ | $6.5 \times 10^{-14}(\pm 50\%)$ |
| FWHM (µm)                     | 0.0236 ± 0.0008 | 0.0165$^{+0.0045}_{-0.0015}$ | 0.0165$^{+0.0045}_{-0.0015}$ |
| FWHM (km s$^{-1}$)            | 3150 ± 100 | 2200$^{+1000}_{-2000}$ | 2200$^{+1000}_{-2000}$ |

### Table 2

**Properties of cK39**

| Property                     | $h_{50} = 1$, $q_0 = 0.5$ | Assumed Line |
|------------------------------|---------------------------|--------------|
| Redshift                     | 0.199 ± 0.002             | $Pz$ |
| Size (kpc): east-west separation | 5.5                      | 10           |
| Survey volume (Mpc$^3$)      | 1555 $h_{50}^{-2}$        | 28,500 $h_{50}^{-2}$ |
| Line luminosity (ergs s$^{-1}$ Å$^{-1}$) | $1.2 \times 10^{17}$ $h_{50}^{-2}$ | $2.7 \times 10^{17}$ $h_{50}^{-2}$ |
| Equivalent width (Å)         | 360                       | 125          |
| SFR ($M_\odot$ yr$^{-1}$)    | $9 h_{50}^{-2}$           | $240 h_{50}^{-2}$ |
| $A_v$ (mag)                  | 4–8                       | 0–3          |
| $\rho$ (Gpc$^{-3}$)          | $3 \times 10^{-5}$–$3 \times 10^{-6}$ | $1.6 \times 10^{-5}$–$1.6 \times 10^{-6}$ |

*The calibration uncertainties are ~ 50%.

### Table 3

**Comparison of Object Properties**

| Property                      | MTM 095355+545428 | HR 10 | MS 1512–cB58 | Hawaii 167 |
|------------------------------|-------------------|-------|--------------|------------|
| Redshift                     | 2.43              | 2.5   | 1.44         | 2.72       | 2.36       |
| $\Sigma$ (objects deg$^{-2}$) | 14–1400           | 150–15,000 | 1.7–170      | 0.11–11    | 2.2–220    |
| $K$                          | 18.5              | 19.5  | 18.4         | 17.9       | 17.2       |
| Color                        | $R - K' = 5.5$   | $I - K = 4.2$ | $I - K = 6.5$ | $I - K' = 2.0$ | $I - K' = 2.8$ |
| Size (kpc, $h_{50}^2$)       | $16 \pm 3$       | $\sim 5$ | 5.6         | 23         | <4         |
| $L_{\text{R}}$ (erg s$^{-1}$, $h_{50}^2$) | $2.7 \times 10^{43}$ | $1.1 \times 10^{43}$ | $1.2 \times 10^{43}$ | $3.2 \times 10^{43}$ | $2.4 \times 10^{44}$ |
| Rest $W_{\text{R}}$ (Å)      | 125               | 102   | 600          | 58         | 320        |
| FWHM (km s$^{-1}$)            | $\sim 3000$      | < 3000 | 7000 ± 3000  | ...        | 5000       |
| SFR ($M_\odot$ yr$^{-1}$, $h_{50}^2$) | 240               | 100   | > 100        | > 290      | > 2000     |
But the emission line made it possible to argue that HR 10 could not be an elliptical galaxy, as proposed by Hu & Ridgway (1994) on the basis of the colors alone; it must contain young stars or an active nucleus. The irregular shape and the strong rest-frame blue (observed 1 μm) flux density make HR 10 more likely to be a reddened Sb galaxy with $A_V \sim 1.8-2.5$. Although cK39 was discovered first via its emission line, it is also a red object with properties and contradictions similar to HR 10. Correcting the $240 \ h_5^{2.6}$ SFR of cK39 for the extinction derived from the red color yields a total SFR that could be as high as $10^3 \ M_\odot \ yr^{-1}$. While the 10 kpc separation of the two components is consistent with a relative velocity of 100 km s$^{-1}$ over 0.1 Gyr, starbursts of this magnitude cannot last for long before exhausting their material; an entire elliptical galaxy could be created in 0.1 Gyr at the $10^3 \ M_\odot \ yr^{-1}$ rates implied by the observations. In addition, the age of the universe at $z = 2.43$ is about 3 Gyr for our adopted cosmology. If the lifetime of the object as observed is only 0.1 Gyr, there would have to be roughly 30 times as many of these objects as estimated in Table 2 to make the probabilities consistent. The density of the parent population would then be $5 \times 10^{-4} \ Mpc^{-3}$, about equal to the number of galaxies brighter than $L^*$ estimated using the usual Schechter function (Schechter 1976). This density is quite high and would imply that objects like cK39 could account for the bulk of the star formation in the early universe. Many galaxies would create their stars in a short burst but intense bursts. However, there are currently no well-documented starbursts of this magnitude that have not later been shown to contain an active nucleus, and a number of surveys targeting intense starbursts at high redshift have failed to turn up any significant population of objects.

One viable alternative to a massive starburst, and one which is consistent with the data, is that an AGN produces some or all of the H\textalpha + [N II] emission. The strength of the H\textalpha + [N II] line would imply a medium-luminosity AGN, quite commonly found at redshifts of $\sim 2$, and would reduce or eliminate the need to invoke such large star formation rates. While the line emission in cK39 appears extended in the narrowband image, there are a number of high-redshift radio galaxies with significantly extended line emission powered by an active nucleus or radio jets without large amounts of star formation. The line width is also consistent with AGN line widths, and active nuclei are often found in disturbed systems consistent with an ongoing or recent merger. It is unlikely that we should find an AGN within the survey volume, however; the a priori probability is on the order of 0.02, assuming no extinction at K, a spectral index of $-0.5$ to give an absolute magnitude $M_B = -26.3$, and Bolye's (1991) luminosity function for quasars. The original survey (TMB96) specifically targeted the environments around known quasars and radio galaxies, so this probability estimate ignores any possible contributions from clustering. In the Keck K-band image (Fig. 1), both components appear extended, and neither appears strongly dominated by the presence of a point source.

A third possibility is that a faint foreground galaxy or cluster amplifies the line flux from cK39 through gravitational lensing. The luminous object FSC 10214 + 4724 (Rowan-Robinson et al. 1991) is an example of how gravitational lensing can distort the interpretation of data taken with low spatial resolution and poor signal-to-noise ratios (Goodrich et al. 1996). To magnify by a factor of order 10, the foreground galaxy must be almost coincident with cK39 along the line of sight. The faint R-band detection could be such a galaxy, which might then redden the light from cK39. If so, it would be fainter than typical lensing galaxies found to date. The Keck images show no hint of the arc morphology that describes most strongly lensed objects nor any obvious foreground lens, even though the seeing-limited spatial resolution is quite good, less than 0.7". We note that the apparently symmetric galaxy MS 1512–cB58 exhibits arcs in a HST image and is, therefore, a gravitational lens (Bechtold 1997, private communication).

4. CONCLUSIONS

The emission-line object TMB 0149–cK39 appears to be a pair of galaxies undergoing a merger at a redshift of 2.4. If cK39 derives a substantial part of its luminosity from star formation, the formation rate is as high as $1000 \ M_\odot \ yr^{-1}$, an exceptionally large value that is rarely seen in other star-forming galaxies. On the other hand, the system could contain at least one active nucleus, perhaps with some contribution from star formation. The individual components appear to be 6 and 7 kpc in extent, with centers separated by 10 kpc, consistent with a merger-induced fuelling of nuclear activity. An extinction of $A_V \sim 1.7$ is necessary to produce the observed $R - K$ color of 5.5, requiring the presence of a significant amount of dust in order to suppress the ultraviolet light and redden the galaxies. Although gravitational lensing by a foreground galaxy or cluster of galaxies could enhance the brightness of the emission, there is little evidence of such a galaxy or cluster along the line of sight. The growing number of very red galaxies at high redshift indicates that there are new populations uncovered only in infrared surveys (e.g., Graham & Dey 1996; Malkan et al. 1996 and references therein). In a separate paper (Thompson et al., in preparation), we present statistics that show extremely red objects ($R - K > 6$) have a sky density on the order of 500 deg$^{-2}$ for $K' \leq 19.75$, so cK39 may, indeed, be part of a larger population. These results underscore the importance of employing a number of different techniques for exploring the epoch of early star formation and demonstrate that a better understanding of these objects is important to an understanding of galaxy formation in the early universe.

We are grateful to T. Herbst and the staff at UKIRT for help with the UKIRT observations, obtained through the UKIRT/MPIA collaboration, as well as the staff at the W. M. Keck Observatory for their support during the Keck runs, and to the staff at Calar Alto for support of the original survey. We profited from discussions with A. Burkert, M. Malkan, K. Meisenheimer, C. Steidel, M. Schmidt, and S. White during the preparation of this paper. An anonymous referee provided thoughtful comments that helped us improve the final manuscript. S. G. D. wishes to acknowledge support from the Bresseler Foundation. This research was supported by the Max Planck Society.
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