AN EXTREMELY LUMINOUS GALAXY AT $z = 5.74$

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ABSTRACT

We report the discovery of an extremely luminous galaxy lying at a redshift of $z = 5.74$, SSA22-HCM1. The object was found in narrowband imaging of the SSA22 field using a 105 Å bandpass filter centered at 8185 Å during the course of the Hawaii narrowband survey using the Low-Resolution Imaging Spectrograph (LRIS) on the 10 m Keck II telescope, and it was identified by the equivalent width of the emission [W$_{e}$ (observed) $= 175$ Å, flux $= 1.7 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$]. Comparison with broadband colors shows the presence of an extremely strong break ($>4.2$ at the $2 \sigma$ level) between the $Z$ band above the line, where the AB magnitude is 25.5, and the $R$ band below, where the object is no longer visible at a $2 \sigma$ upper limit of 27.1 (AB magnitudes). These properties are only consistent with this object’s being a high-$z$ Ly$_\alpha$ emitter. An 18,000 s spectrum obtained with LRIS yields a redshift of 5.74. The object is similar in its continuum shape, line properties, and observed equivalent width to the $z = 5.60$ galaxy HDF 4–473.0, as recently described by Weymann et al., but is 2–3 times more luminous in the line and in the red continuum. For $H_0 = 65$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = (0.02, 0.5)$, we would require star formation rates of around $(40, 7) M_\odot$ yr$^{-1}$ to produce the UV continuum in the absence of extinction.

Subject headings: cosmology: observations — early universe — galaxies: evolution — galaxies: formation

1. INTRODUCTION

Studies of high-redshift galaxies have now advanced well beyond $z = 5$, with the confirmation of a number of such systems using the Keck II 10 m telescope over the past year (Dey et al. 1998; Hu, Cowie, & McMahon 1998; Weymann et al. 1998). A key issue for future studies of distant, early star-forming galaxies is the incidence of bright, high-redshift galaxies in the general field population. Here we report on the discovery of a luminous $z = 5.74$ Ly$_\alpha$-emitting galaxy in the Hawaii Survey Field SSA22.

As part of our deep imaging searches to systematically identify and study high-redshift galaxies in blank field surveys (Cowie & Hu 1998; Hu et al. 1998) and fields around high-redshift quasars (Hu, McMahon, & Egami 1996; Hu & McMahon 1996), we have been conducting deep narrowband imaging on the Keck II 10 m telescope to look for high-redshift Ly$_\alpha$-emitting galaxies. Previous results from the deep Low-Resolution Imaging Spectrograph (LRIS) narrowband surveys at 5390 Å (or $z_{13a} \sim 3.4$) and 6741 Å (or $z_{13a} \sim 4.5$) have been reported in Cowie & Hu (1998) and Hu et al. (1998). The present object, which we will refer to as SSA22-HCM1, was discovered during the course of a $z \sim 5.7$ search using a 105 Å bandpass narrowband filter centered on 8185 Å. The results of this survey will be reported in detail elsewhere (Hu, Cowie, & McMahon 1999). We have chosen to describe this object separately because of its high luminosity, which places it at the high end of the luminosity function for optically selected galaxies at all redshifts. If the light is produced by massive star formation with a Salpeter mass function, the inferred rate is $40 M_\odot$ yr$^{-1}$ $h_{78}^2$ for $q_0 = 0.02$.

2. OBSERVATIONS

Deep multicolor imaging data with LRIS (Oke et al. 1995) on the Hawaii Survey Field SSA22 have been described in Cowie & Hu (1998) and Hu et al. (1998). The $z = 5.7$ Ly$_\alpha$ survey of this region was carried out with narrowband exposures in the 8185 Å filter obtained on UT 1998 August 21 as a sequence of nine 1200 s exposures. The present work augments the continuum data at the redder wavelengths by doubling the $I$-band exposures (seven 360 s exposures taken UT 1998 August 21) and by obtaining a line-free red continuum through an RG850 filter (hereafter referred to as Z band) on UT 1998 September 17 as a dithered sequence of 18 exposures of 330 s each. Conditions were photometric on these nights, with image FWHM $\sim$0.75–0.77 for the Z-band exposures and $\sim$0.7–0.75 for the I- and 8185/105 narrowband exposures. These data were calibrated with spectrophotometric standards (Feige 110, Feige 15, and HZ4: Massey et al. 1988; Massey & Gronwall 1990; Oke 1990; Stone 1996) and Landolt standards (Landolt 1992). The net exposure times for the combined LRIS imaging in these bands are summarized in Table 1, and multicolor images of SSA22-HCM1 are shown in Figure 1.

The Z band is similar to the $z'$ filter used by the Sloan Digital Sky Survey (Frei & Gunn 1994; Fukugita, Shimasaku, & Ichikawa 1995; Fukugita et al. 1996) and to the Gunn $z$ (Schneider, Gunn, & Hoessel 1983; Fukugita et al. 1995) and Gunn $z_{12}$ (Schneider, Schmidt, & Gunn 1989; Fukugita et al. 1995) bands used in high-$z$ quasar searches. The combined filter + LRIS optics + CCD response curve yields an effective wavelength $\lambda_{eff} = 9271$ Å (9166 Å for a flat $f$ source) and FWHM = 1430 Å, with a peak response at 8811 Å. The net response is less than 1% of this maximum value at 8185 Å, so the Z band provides a long-wavelength continuum measurement uncontaminated by emission in the 8185 Å narrowband filter.

Candidate Ly$_\alpha$ emitters were selected for spectroscopic follow-up from sources in the 5 Å narrowband catalog with observed equivalent widths greater than 80 Å in the observed frame, which were also undetected in the V band down to the $2 \sigma$ limit of 27.5. For the current work, photometric measurements are made over matched 2″ diameter apertures, in contrast to the 3″ diameter apertures used in earlier work (Cowie & Hu

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TABLE 1

PHOTOMETRIC DATA ON THE $z = 5.74$ GALAXY SSA22-HCM1

| Parameter | $W_l$(observed) (Å) | Flux (ergs cm$^{-2}$ s$^{-1}$) | $Z$(AB)$^+$ | $N$(AB)$^+$ | $R$(AB) | $V$(AB) | $B$(AB) | $K$(AB)$^+$ |
|-----------|---------------------|-------------------------------|------------|-------------|--------|------|------|--------|
| Measured value ...... | 175 | 1.7 (−17) | 25.5 | 24.5 | 26.6 | −28.1 | −29.9 | 29.8 | −25.0 |
| (1 σ) ................. | 20 | 2.2 (−18) | 26.5 | 27.2 | 27.3 | 27.8 | 28.2 | 28.3 | 24.9 |
| $t_{exp}$ (s) ............ | ... | ... | 5940 | 10800 | 5020 | 4320 | 5600 | 2440 | 14400 |

Note.—2" diameter aperture magnitudes. A negative magnitude here indicates that there is a negative flux in the aperture. The 1 σ limits are derived from random aperture sampling off of sources in the composite Keck exposures for each band ($t_{exp}$ given in seconds).

$^+$ Schott RG850 filter, $\lambda_{eff} = 9271$ Å, FWHM = 1430 Å.

$^+$ 8185/105 narrowband filter.

$^+$ Upper limit, NIRC data taken under nonphotometric conditions; $H + K$ observations from UH 2.2 m and CFHT of near comparable depth used as cross check.

1998; Hu et al. 1998), and are corrected to total magnitudes following Cowie et al. (1994). The 1 σ error limits given in Table 1 and in Cowie & Hu (1998) and Hu et al. (1998) are determined from flux measurements in random aperture samples laid down at positions away from identified sources, since in the deep exposures (see Fig. 1) magnitude limits are set by the background faint source population. These values can be up to ~0.7 mag brighter than limiting magnitudes estimated by background pixel statistics (e.g., Dey et al. 1998), depending on color bandpass.

Spectra of candidates were obtained on LRIS in multislit masks with the 300 line mm$^{-1}$ grating on the nights of UT 1998 September 16 and 18 and with the 400 and 150 line mm$^{-1}$ gratings on the nights of UT 1998 September 17 and October 22. Infrared images of SSA22-HCM1 at $K'$ were obtained with NIRC on the Keck I telescope in 15,000 s on UT 1998 October 4 under nonphotometric conditions. These were cross-calibrated with $K'$ images of the SSA22 field of near comparable depth from the Hawaii Survey program based on imaging with the 1024$^2$ University of Hawaii (UH) IR camera QUIRC (Hodapp et al. 1996) at the UH 2.2 m telescope and the Canada-France-Hawaii 3.6 m telescope (CFHT). However, the 1 σ detection limits given in Table 1 are based on the QUIRC survey data alone.

3. DISCUSSION

The SSA22-HCM1 galaxy is characterized by both a strong color break and strong Ly$\alpha$ emission. The high contrast of this object in the emission-line bandpass can be seen in the narrowband 8185/105 Å panel of Figure 1 and in the extended appearance of SSA22-HCM1 in this band compared with the red $Z$ and $I$ continuum bandpass images. The strong continuum break is seen in the spectral energy distribution (Fig. 2), with at least a factor of 4.2 jump based on the $(R − Z)$ color difference. It is completely absent in the $B$-, $V$-, and most signifi-

![Fig. 1.—Multicolor $B$, $V$, $R$, $I$, $Z$, and narrowband 8185/105 Å images taken with LRIS on Keck of the $z = 5.74$ object, SSA22-HCM1 [R.A. (1950): 22°15′05.97″; decl. (1950): −00°01′12.79″]. Each panel is 30" on a side. The positions of the sources are marked, with a separation of about 2′′ between tick marks. The $I$-band image is weakly contaminated by line emission, but most of the light arises from the continuum, while the $Z$ band is free of emission. The object is absent at $B$, $V$, and $R$ in these extremely deep Keck LRIS images, which reach 1 σ limits of $B = 28.3$, $V = 28.2$, and $R = 27.8$ for a 2" diameter aperture (magnitudes in the AB system). $I$(AB) for SSA22-HCM1 is 26.5, and $Z$(AB) is 25.5.](image)
Here strong Ly
respectively. This gives a formal ratio, similar to the
using the rest-frame wavelength range 1050±1170 Å for
the rest-frame wavelength is a line-free continuum measurement. We use the R and Z bands to
measure the discontinuity. The strong break (2σ upper limit of 0.23 across the line) combined with the strong emission line is a signature for Lyα.

cantly, R-band images. For the R-band nondetection we use the 2σ estimate of 27.1 (AB magnitude) to set the lower limit of (R−Z) > 1.6 and estimate a minimum break strength. The break may also be seen in the spectral data, and in Figure 3 we show a composite 10,800 s LRIS spectrum. The heavy lines show the averaged continuum values for the wavelength regions sampled above and below the strong emission feature, and while there is a significant positive signal above the line, the spectrum is consistent with there being zero flux at shorter wavelengths. Figure 4 shows the region of the 8190 Å emission line in the unsmeared summed spectrum of all observations made with the 300 line mm⁻¹ grating (18,000 s). The line is unresolved at an instrumental resolution of 12.4 Å FWHM, corresponding to a velocity σ < 200 km s⁻¹. Instrument problems prevented acquisition of sufficient higher resolution observations to test for line asymmetry. Examination of the spectral data provides a rough consistency check of the continuum and line properties. Following Oke & Korycansky (1982), we measure the flux deficit parameter

\[ D_α = \left( 1 - \frac{f_α(\text{observed})}{f_α(\text{continuum})} \right) \]

using the rest-frame wavelength range 1050–1170 Å for \( f_α(\text{observed}) \) and 1250–1370 Å for the red observed continuum. These yield \( f_α = 0.050 ± 0.048 \) and \( f_α = 0.244 ± 0.054 \) μJy, respectively. This gives a formal ratio \( D_α = 0.79 \), similar to the limit obtained with the Z- and R-band filters (\( D_α > 0.76 \)), and again it is the limits on the nondetection of the galaxy at shorter wavelengths that constrains the lower limit on \( D_α \). The errors in these faint continuum measurements based on spectroscopy are dominated by night-sky subtraction and systematic errors and are not Gaussian. The filter photometry provides a more robust and conservative determination of the continuum break. However, the emission-line flux calculated from the spectroscopic data (2.0 ± 0.1 × 10⁻¹⁷ ergs cm⁻² s⁻¹) and the continuum magnitudes (\( AB_{1050–1170, \text{rest}} < 27.0 \) and \( AB_{1250–1370, \text{rest}} = 24.4 ± 0.3 \)) agree with the R and Z continuum magnitudes listed in Table 1 and are consistent with a flat \( f_α \) spectrum plus a break. Identifying the line with Lyα, we find the redshift of \( z = 5.74 \). The remaining properties of the line are best determined from the imaging data, and we find from these that it has an observed equivalent width of 175 Å and a flux of \( 1.7 \times 10^{-17} \) ergs cm⁻² s⁻¹.

The object most similar to SSA22-HCM1 among those known in the current literature is the \( z = 5.60 \) galaxy HDF 4–473.0 (Weymann et al. 1998), which shows both the strong continuum break between the F606W and F814W bands (and infrared F110W and F160W bands at J and H) and an emission line of roughly comparable equivalent width and flux, corresponding to Lyα at \( z = 5.60 \). The Lyα flux of SSA22-HCM1 is approximately twice as strong, and the continuum above the break a factor of 3 times more luminous than for this \( z = 5.60 \) galaxy, using the near-IR magnitude of HDF 4–473.0, AB(F110W) = 26.64 to approximate its continuum. In comparison, while the estimated continuum magnitudes above Lyα for the two Spinrad et al. galaxies are comparable to that of SSA22-HCM1 (24.9 and 25.7 AB mag for 3–951.1 and 3–951.2 vs. 25.5, estimated from our Z-band observations), neither of these systems shows any emission, while the Dey et al. object, RD1, has much higher equivalent width (600 Å) and a fainter continuum above Lyα (26.3 AB magnitudes based on the much more uncertain spectroscopic estimates).

![Fig. 2.—Spectral energy distribution for SSA22-HCM1 obtained using LRIS and showing the bandwidths and errors for measurements in B, V, R, I, narrowband 8185/105 Å (emission), RG850 (line-free continuum longward of the emission), J, and H = K'. Significantly, the object has no flux in the R band, where strong Lyα forest absorption is expected to be present. The I band is slightly contaminated by Lyα emission, but the Z-band measurement at longer wavelengths is a line-free continuum measurement. We use the R and Z bands to measure the discontinuity. The strong break (2σ upper limit of 0.23 across the line) combined with the strong emission line is a signature for Lyα.](image)

![Fig. 3.—Spectrum of the redshift \( z = 5.74 \) galaxy SSA22-HCM1 obtained in a 10,800 s exposure using the 300 line mm⁻¹ grating on LRIS. The heavy lines show the averaged continuum values at the indicated rest-frame wavelengths above and below the line.](image)

![Fig. 4.—Spectral region around the emission. The complete summed LRIS observations from 18,000 s total exposure with the 300 line mm⁻¹ grating. The instrumental resolution (12.4 Å FWHM, determined from Gaussian profile fits to night-sky lines) is overplotted with the dashed curve. The line is unresolved at a velocity \( σ < 200 \) km s⁻¹.](image)
Since resonant scattering enhances the effects of extinction, converting the Lyα emission into a massive star formation rate entails large uncertainties. For the present calculation, we assume that extinction may be neglected in computing the required massive star formation rates, which then constitute a minimum estimate. The maximum values obtained from ionization by a massive star population lie in the 100–200 Å range (Charlton & Fall 1993; Valls-Gabaud 1993). Up to roughly half the rest-frame emission may be eaten away by the Lyα forest, and applying such a correction factor would give values above 50 Å, as compared to the Weymann et al. rest-frame equivalent width corrected for hydrogen absorption) of 90 Å. Assuming case B recombination, we have $L(\text{Ly}α) = 8.7 \times 10^{42} \text{ergs s}^{-1} \text{M}_\odot \text{yr}^{-1}$. For $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.02$, the observed line flux of $1.7 \times 10^{-17} \text{ ergs cm}^{-2} \text{s}^{-1}$ translates into a star formation rate of $19 \text{ M}_\odot \text{yr}^{-1}$. (For $q_0 = 0.125$, the line luminosity would be a factor of 1.9 times lower, and for $q_0 = 0.5$, a factor of 6 times lower than for the present calculation.) These values, which are uncorrected for dust extinction, are consistent with the maximum values seen in the estimates for the systems up to $z \sim 4.5$ in the Lyman break galaxies studied to $I(AB) < 25$, which have rest-frame equivalent widths up to 80 Å (Steidel et al. 1999). For $H_0 = 65 \text{ km s}^{-1} \text{ Mpc}^{-1}$ and $q_0 = 0.02$, the continuum luminosity at rest-frame 1500 Å is $9.7 \times 10^{-20} \text{ ergs cm}^{-2} \text{s}^{-1} \text{ Å}^{-1}$ and corresponds to a star formation rate (e.g., Madau, Pozzetti, & Dickinson 1998) of roughly 40 $\text{M}_\odot \text{yr}^{-1}$, consistent with the lower limit set by the emission-line calculation.

Because SSA22-HCM1 is so bright in Z, it is of interest to estimate the number of potential high-redshift ($z > 5$) objects from $(R-Z)$ color statistics using a $Z < 25.25$ sample. (Although this Z-band criterion is not sufficiently deep to include SSA22-HCM1, the $z = 5.60$ galaxy HDF 4-473.0 [Weymann et al. 1998] or the $z = 5.34$ emission-line object [I(AB) = 26.1; Dey et al. 1998], the threshold is only a few tenths of a magnitude from reaching the brighter two of these objects.) Line blanketing from the intergalactic Lyα forest quenches the flux below redshifted Lyα by more than an order of magnitude, based on extrapolations from forest simulations (e.g., Zhang et al. 1997). For the SSA22 LRIS field over a 32 arcmin' region there are only four objects with $(R-Z) > 2.75$ and $Z(AB) < 25.25$, with typical $Z(AB) > 25$, with a similar number in an LRIS field crossing the Hubble Deep Field (HDF), for which the effective Z exposure is roughly twice as deep. Such objects may be $z > 5$ galaxies or highly reddened objects; the color boundary lies marginally above the range of possible M star contaminants, which might be distinguished by compactness criteria. In the HDF, the $(R-Z)$ method recovers the combined V-dropout objects, HDF 3–951.1 and HDF 3–951.2, which Spinrad et al. (1998) identify as a $z \sim 5.34$ galaxy pair based on a spectral break. (Both the estimated redshift and discontinuity of greater than 8 are based on the LRIS continuum spectrum, which has no emission features.) Our $Z$ and $R$ imaging gives $(R-Z) \sim 3.1$ for this object, similar to the colors of the Lyα bright objects. Thus, it appears that very deep Z imaging can reveal the very brightest members of the redshift 5 population and represents a viable alternative way to approach the problem.

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