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A FIELD GALAXY AT A PROBABLE REDSHIFT OF 3.38

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ABSTRACT

In a previous *Letter* we identified a population of flat spectrum (f_ν) galaxies that increasingly dominate the population of faint galaxies at $I \gtrsim 23$ and argued that these are responsible for a large fraction of the massive metal-producing star formation in the history of the universe. We have now obtained a spectrum of one of these objects and tentatively identify it as lying at $z = 3.38$, on the basis of a Lyα line and Lyman break. The existence of the break has also been confirmed by ultraviolet photometry. The presence of a Lyα forest decrement and a marginal C IV line are consistent with this identification.

Subject heading: galaxies: redshifts

I. INTRODUCTION

In a recent *Letter* (Cowie *et al.* 1988, hereafter Paper I) we used data from a multicolor (*BVIK*) deep survey (Lilly, Gardner, and Cowie 1989; Gardner *et al.* 1989) to identify a population of galaxies with nearly flat f_ν spectral energy distributions in the *BVI* colors. This population is found at magnitudes fainter than $I = 23.0$ and is a substantial subset of the blue population which had been found at these magnitudes in previous deep surveys (Koo 1986; Tyson 1988). The colors of these objects (typically $B-V \approx 0.2$, $V-I \approx 0.8$) are similar to nearby starbursting galaxies (e.g., Johansson 1988) and are bluer even than Im galaxies, suggesting that they are dominated by a young stellar population.

The flat spectrum population is of considerable interest because of its very high surface density on the sky. As described in Paper I, for $23 < I < 24$, there are approximately 1×10^4 such objects per square degree of sky, giving an average extragalactic background light on the sky of at least $1\text{–}2 \times 10^{-25}$ ergs cm^{-2} s^{-1} deg^{-2} Hz^{-1}. Independently of details of cosmology, the extragalactic background light (EBL) contribution of young star-forming systems in the flat spectrum wavelength range is a linear measure of their total contribution to the present metal density of the universe (Lilly and Cowie 1987; Cowie 1988) *regardless* of the epoch at which this occurs. Thus we can infer that the brightest of these flat-spectrum systems alone made a considerable fraction (around $20h^{-2}$%, where $h = H_0/50$ km s^{-1} Mpc^{-1}, but with much uncertainty) of all the observed metals in the universe. In fact, because the observed systems may constitute only the luminous tail of the luminosity function, and hence may contribute only a fraction of the total EBL of the population, the likelihood is that these objects represent the major producers of metals in the history of the universe. While these extremely powerful and model-independent arguments can show that the flat spectrum galaxies are of critical cosmological importance, the broad-band spectral energy distributions give only the crudest information about the redshift of these objects. In Paper I we inferred only that $z < 3.5$ (since, beyond this redshift, the Lyman-continuum break moves through the *B* band). However, without direct spectroscopic redshifts, the objects could lie at $z \sim 0$ and constitute an immense population of low-luminosity starbursters, or could lie $z \sim 3$ and be massive young galaxies.

We have now obtained a spectrum of one of these extremely faint objects (SSA 22–24 of Paper I, with $B \sim 24$). As we shall discuss below, this object has a probable redshift $z = 3.38$ and suggests that some of the flat spectrum sources may indeed be early rapid star-forming stages of massive galaxies.

II. OBSERVATIONS

The observations were obtained using the University of Hawaii wide field grism spectrograph with a low-noise TI 800 × 800 CCD detector on the 3.6 m Canada-France-Hawaii Telescope during 1988 July 15–16. The projected pixel size was 0″.38 by 6.90 Å with a slit length of 225″, a slit width of 3″, and a useful wavelength coverage from just below 3800 Å to just above 8200 Å. The peak response of the system lies near 5000 Å and represents a throughput from sky to collection of around 15%. Measured resolutions were 1″.5 spatially and 49 Å spectrally. The faint galaxy SSA 22–24 is located in our SSA 22 survey field, which is at right ascension (1950) $22^h15^m00^s$ and declination (1950) 00°00′00″. (The declination was incorrectly reported as −01°00′00″ in Paper I.) This is a region with low galactic reddening ($0.03 < E_{B-V} < 0.06$ according to the H I column density maps of Burstein and Heiles 1982). A finding chart of SSA 22 is shown in Figure 1*a*. The slit of the spectrograph was placed over SSA 22–24 by means of a rotational offset around the 19th mag star designated A on Figure 1. The relative position of SSA 22–24 and two bright (19th mag) objects 1′–2′ away, labeled A and Z, was carefully measured off of our deep CCD images and the spectrograph slit was positioned at an angle of 75°.3 relative to the line joining these two objects, as shown in Figure 1*a*. An *I*-band image of the SSA 22 field is shown in Figure 1*b*; the objects on the SSA 22 field that were crossed by the slit are labeled. SSA 22–24 is object D on Figure 1*b*.

Over the course of two photometric nights a 406 minute exposure was obtained consisting of seven integrations, each of which was sky-limited. Each exposure was shifted along the slit to allow us to use median flat-fielding techniques and to remove any artifacts associated with the device. The data were median sky–flattened, registered, and then added, filtering out cosmic rays, hotspots, and other artifacts. The data were then geometrically distorted to align the night sky lines along the

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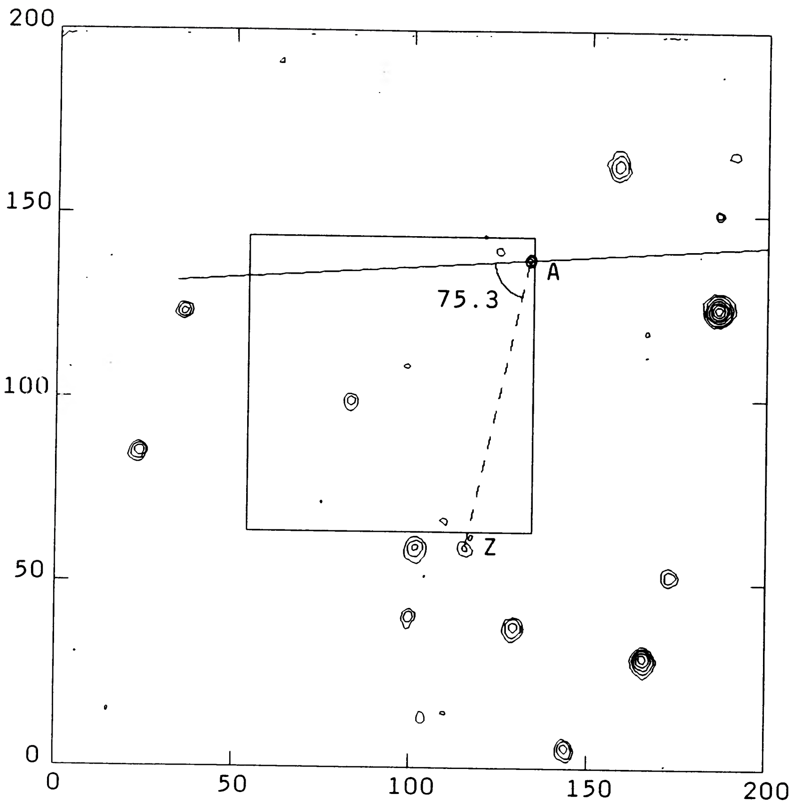

FIG. 1*a*

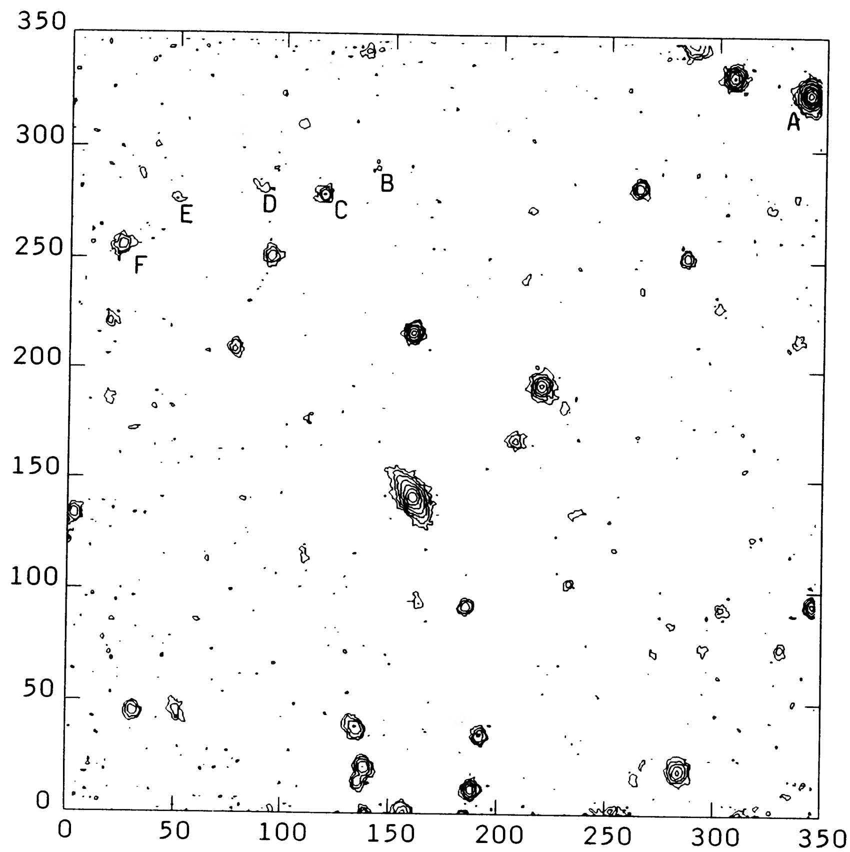

FIG. 1*b*

FIG. 1.—(*a*) Finding chart for the SSA 22 field at $22^h15^m00^s$, 00°00′00″ (1950) showing the objects (A, Z) used in positioning the slit. The pixel size is very approximately 1″. North is roughly to the top, and east is roughly to the left. (*b*) An *I*-band image of SSA 22, labeling the objects crossed by the slit. SSA 22–24 is object D. The pixel size is 0″.214. Orientation is as in (*a*).

rows and a third-order sky subtraction performed, excluding detected objects. The data were finally flux-calibrated and wavelength-calibrated using observations of the spectrophotometric standard BD +284211, which contains many sharp H and He lines (Massey *et al.* 1988). The wavelength calibration was tested against the strong night sky lines and found to be accurate to about 2 Å, while the flux calibration was tested against the *BVI* photometry of star A and found to be good to better than 0.1 mag over this wavelength range. Approximately 26 objects can be seen along the slit. Four of the brightest eight objects lie on the SSA 22 field, and four lie in the extensions of the slit to either side of it.

The spectrum of the target object SSA 22–24 (D) is shown in Figure 2 both in raw form (Fig. 2*a*) and flux-calibrated (Fig. 2*b*). The total counts per resolution element in SSA 22–24 near 5000 Å are about 4200 electrons, while the sky background is about 74,000 electrons, giving a nominal signal-to-noise ratio of about 6:1 in each spectral pixel and 15:1 in each spectral resolution element. A similar signal-to-noise ratio is inferred in practice by comparing the spectrum with a nearby blank sky region, as is shown in Figure 2*a*. The spectrum of SSA 22–24 has a moderately strong line at 5333 Å and appears to drop abruptly to a low value below 4058 Å. (We refer to this subsequently as "the break.") The equivalent width of the emission line is 26 Å, and its FWHM is 51 Å so that it is essentially unresolved. The limit on its intrinsic width is $\Delta\lambda(\mathrm{FWHM}) \lesssim 14$ Å or $\Delta v(\mathrm{FWHM}) \lesssim 750$ km s^{-1}.

Because the break occurs at the very short-wavelength end of our spectrum where the sensitivity is dropping rapidly and where defocusing effects are becoming significant, we felt it was crucial to confirm this feature and to make sure that the break continued to still shorter wavelengths. We therefore obtained a 20 hr exposure through a U' filter ($\lambda_c = 3400$ Å, $\Delta\lambda = 275$ Å) using the TI CCD camera on the University of Hawaii 88 inch (2.24 m) telescope in 1988 October. The data were obtained over four nights in photometric conditions with 0".6 seeing. The 1 σ AB magnitude ($AB = 48.60 - 2.5 \log f_\nu$ [cgs units]) of this observation was 27.0 in a 3" diameter aperture. The measured

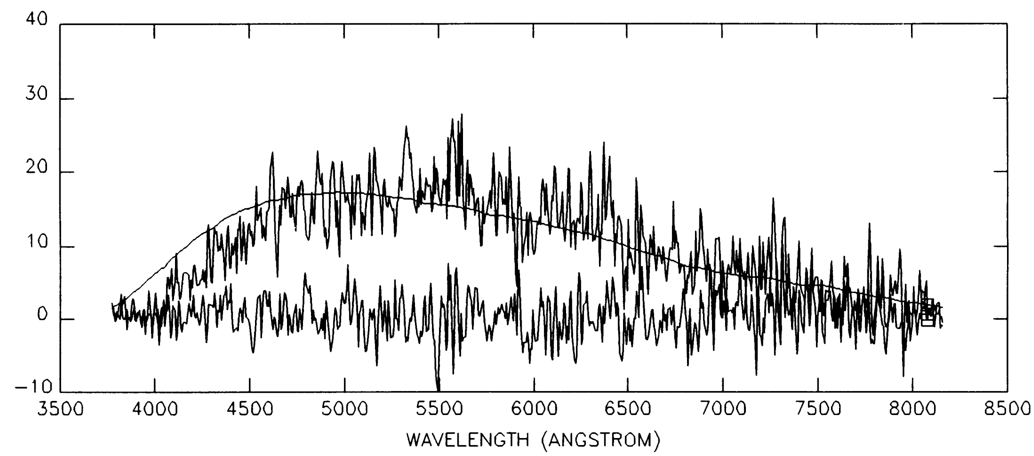

FIG. 2*a*

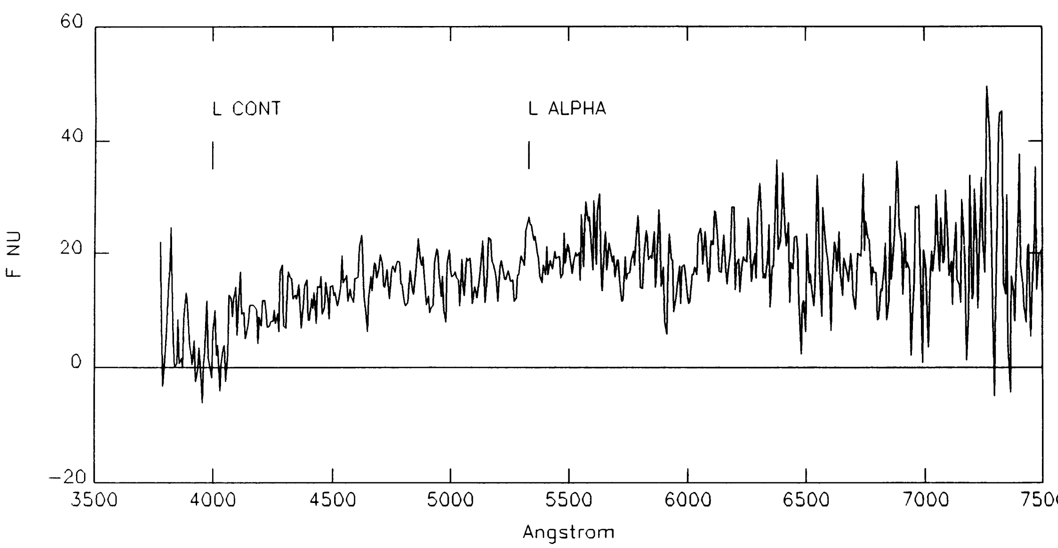

FIG. 2*b*

FIG. 2.—(*a*) The raw spectrum of SSA 22–24 is shown, together with a similarly extracted blank region spectrum at a position 10" from the object, which can be used to gauge the noise level. Also shown superposed over the raw spectrum is the response which would be expected from a flat f_ν spectrum source. (*b*) The flux-calibrated spectrum of SSA 22–24 with line identifications shown for $z = 3.38$.

AB magnitude of SSA 22–24 is $25.15^{+0.25}_{-0.2}$ in U', where the errors are 1 σ limits. This gives a break amplitude lying in the range of 2.6 to 4.2. The broad-band photometric data ($U'BVIK$) is compared with a 70 Å boxcar-smoothed version of the spectrum in Figure 3.

III. DISCUSSION

The emission line is almost certainly not Hβ 4861 or [O III] 5007, since there is no sign of either the [O II] 3727 line or the Hα 6563 + [N II] 6583 complex. The break is also substantially too deep to be a 4000 Å break in a galaxy with a flat spectrum at longer wavelengths (e.g., Hamilton 1985). A more reasonable possibility might be to make the 5333 Å line [O II] 3727, which would place the object at $z = 0.43$. This would put the break at a rest-frame wavelength of 2850 Å, where it could perhaps be partially identified with Mg absorption, but such an abrupt and dramatic drop at this wavelength would be hard to understand in a galaxy of this type. Because of the depth and width of this feature, we feel that the most compelling interpretation is that the break is the Lyman-continuum limit and the emission line is the Lyα line at $z = 3.386$. Support for this is found in the presence of a possible [C IV] 1549 line at 6773 Å ($z = 3.375$) with an equivalent width of 37 Å and a FWHM of 48 Å in the observed frame. (This line appears less significant because it occurs in a noisier part of the spectrum than Lyα where the sky background is much higher, but in fact it lies in a clean part of the spectrum between OH bands, at a wavelength where the sky is low and unstructured. We estimate that the C IV line is a 4 σ detection.)

In Figure 3 we show a comparison with starburst galaxy models kindly supplied by S. White (S. White and G. Bruzual, private communication) which shows an excellent agreement between these models and the shape of the spectrum. In particular, the drop of the specrum below Lyα owing to intrinsic Lyman damping and the dropoff at the Lyman-continuum limit both support the redshift estimated on the basis of the Lyα line. Also shown is the optically thin (little neutral hydrogen) model of Meier (1976) which continues below the Lyman-continuum limit. The observations show slightly more ionizing flux emerging than this model predicts. However, this result is very sensitive to the number of the most massive stars in the system and hence to the choice of the IMF and the upper mass cutoff. The observations can easily be reproduced by slightly increasing the number of stars at the upper mass end.

At this redshift, a strong intergalactic Lyα forest should be present in the spectrum (Steidel and Sargent 1988) which should also produce a drop in the average flux of the object to the short-wavelength side of the Lyα emission line. Since this effect is extrinsic to the object and is found to be relatively invariant in observed quasars, it provides a test of a high-redshift interpretation for any galaxy. In fact, a distinct change can be seen across the emission line in SSA 22–24. We have measured the two Oke-Korycansky indices D_A and D_B, defined as $(1 - f_\nu/f_{\nu 0})$ in the region between Lyβ and Lyα (D_A) and the Lyman-continuum and Lyβ (D_B), where $f_{\nu 0}$ is the flux extrapolated from wavelengths longer than Lyα. (We assumed this was flat and fitted from 5400 Å to 7000 Å.) We find $D_A = 0.25$ and $D_B = 0.49$. In comparison, Steigel and Sargent, in a sample of seven quasars at comparable redshift, find that $\langle D_A \rangle = 0.26$ with a range from 0.17 to 0.49 and $\langle D_B \rangle = 0.42$ with a range from 0.27 to 0.83. The agreement is excellent, but the result is quite uncertain because we do not really know the intrinsic spectrum of the galaxy.

The morphology of SSA 22–24 can be seen in Figure 4. It is a complex object (it may indeed be two or more objects) and it is considerably more extended in the V band. The total size is 3″.5

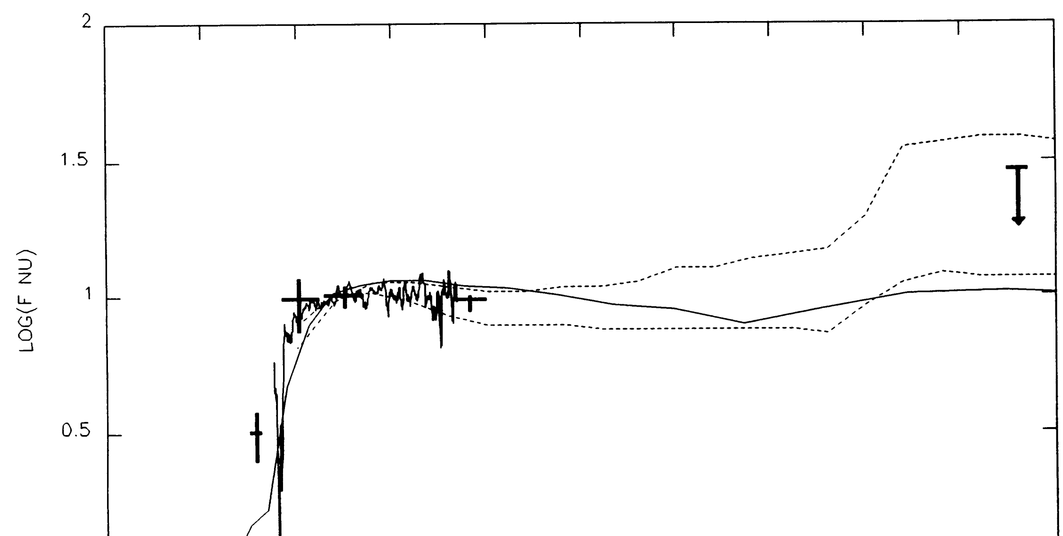

FIG. 3.—A spectrum of SSA 22–24 smoothed with a 70 Å boxcar is shown at a rest wavelength corresponding to $z = 3.38$. Also shown as crosses is the ($U'BVIK$) photometry extracted in apertures corresponding roughly to the slit coverage. (The K band is an upper limit and has been slightly revised upward since Paper I, reflecting our improved understanding of the K-band photometry. For the remaining points, the horizontal bar shows the wavelength range of the bandpass and the vertical bar plausible uncertainties in the fluxes.) The uncertainties in the colors are dominated by morphological changes in the object from bandpass to bandpass which make the magnitudes slightly sensitive to the choice of center and the size and shape of the aperture. The dashed lines schematically show two models of a starbursting galaxy (at different ages and with different IMFs) supplied by S. White and based on computations by S. White and G. Bruzual. The close agreement in shape between the spectrum and the blue end of the models should be noted. The solid line shows Meier's (1976) optically thin protogalaxy model.

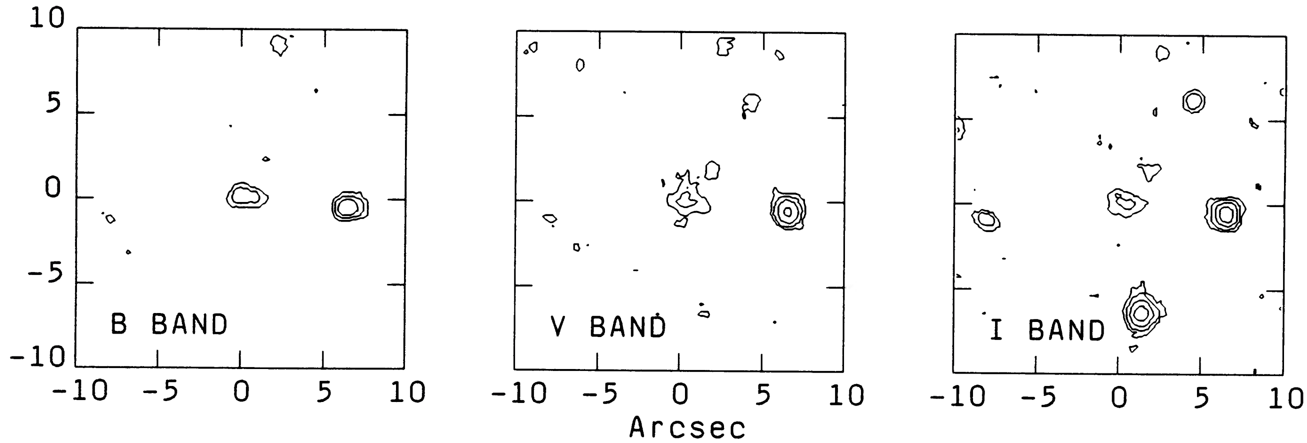

FIG. 4.—Images of SSA 22–24 in *B*, *V* and *I*. The images have been boxcar-smoothed with a 0″.9 box to show the lowest lying contours more clearly, and are contoured at constant surface brightness levels so a flat f_ν object should appear invariant from frame to frame. SSA 22–24 is the object lying at the origin of the *x* and *y* scales. The object is considerably more extended in the *V* band, presumably because of extended line emission from the 5333 Å line seen in the spectrum which lies in this bandpass. Orientation is as in Fig. 1.

to 4″ in the long dimension by about 2″ in the short dimension in the *I* band and about 5″ × 5″ in the *V* band, i.e., about 25–50 kpc, depending on cosmology.

The extended *V*-band image compared to the *I* band or *B* band presumably indicates very extended Lyα emission, a good fraction of which lies outside the slit used in the spectroscopy. About 15% of the *V*-band counts lie outside the *I*-band or *B*-band images, which should raise the Lyα equivalent width to at least 80 Å compared to the 25 Å estimated from the spectrum. Thus, many of the Lyman-continuum photons might actually be reprocessed to Lyα in these outer regions rather than in the core.

If SSA 22–24 is placed at $z = 3.38$, its luminosity ($V = 23.8$) requires that it be forming stars at a rate of very roughly $100h^{-2}\ M_\odot\ \mathrm{yr}^{-1}$, where we have assumed a standard Salpeter IMF and $q_0 = 0.5$ (Baron and White 1987; Cowie 1988). A galaxy with about $10^{11}h^{-2}\ M_\odot$ in baryons would form in 10^9 yr or about $\frac{2}{3}$ of a local Hubble time at this rate and for $q_0 = 0.5$ (Cowie 1988). For $q_0 \sim 0$ the rate rises to about $350h^{-2}\ M_\odot\ \mathrm{yr}^{-1}$ and a massive galaxy would form in only 3×10^8 yr or less than 10% of the local Hubble time. In both cases the time scales are consistent with our seeing the formation of a substantial part of a massive galaxy, though the gross uncertainty in translating the optical luminosities into the star formation rate makes a more detailed comparison inappropriate.

IV. CONCLUSION

On the basis of the evidence we suggest that SSA 22–24 has a probable redshift of $z = 3.38$, and that some of the flat spectrum objects identified in Paper I may plausibly be interpreted as galaxies undergoing major star formation at $z \sim 3$. The spectrum of SSA 22–24 bears a striking resemblance to the classical protogalaxy models of Meier (1976)—that is, it is a roughly flat-spectrum object with an abrupt drop at the Lyman break. The presence of a substantial flux below the Lyman-continuum wavelength and the weakness of the Lyα line suggest that there is relatively little neutral hydrogen in the system and that it is near the optically thin limit.

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