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A REDSHIFT $z \approx 5.4$ Lyα EMITTING GALAXY WITH LINEAR MORPHOLOGY IN THE GRAPES/HUBBLE ULTRA DEEP FIELD

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ABSTRACT

We have discovered an extended Lyα plume (UDF 5225) associated with a compact source at redshift $z \approx 5.4$ in slitless spectroscopic data from the Grism ACS Program for Extragalactic Science (GRAPES) project. The spatial extent of the emission is about 6×1.5 kpc ($1'' \times 0\farcs25$). Combining our grism data and the broadband images from the Hubble Ultra Deep Field (UDF) images, we find a Lyα line flux of $\sim 2.2 \times 10^{-17}$ ergs cm^{-2} s^{-1} and surface brightness $\sim 7 \times 10^{-17}$ ergs cm^{-2} s^{-1} arcsec^{-2}. The UDF images show diffuse continuum emission associated with UDF 5225, including three embedded knots. The morphology of UDF 5225 is highly suggestive of a galaxy in assembly. It is possible that the prominent Lyα emission from this object is due to an active nucleus, and that we are seeing the simultaneous growth through accretion of a galaxy and its central black hole. Follow-up observations at higher spectral resolution could test this hypothesis.

Subject headings: galaxies: formation — galaxies: high-redshift — galaxies: individual (UDF 5225) — galaxies: interactions — galaxies: starburst

1. INTRODUCTION

The Grism ACS Program for Extragalactic Science (GRAPES) project[14] is a slitless spectroscopic survey that exploits the potential of the G800L grism on the *Hubble Space Telescope*'s Advanced Camera for Surveys (ACS) to achieve the most sensitive unbiased spectroscopy yet. GRAPES is targeted in the Hubble Ultra Deep Field (UDF) region, to complement the UDF direct images, which in turn provide the deepest optical imaging to date (S. V. W. Beckwith et al. 2005, in preparation). The GRAPES survey, and in particular our data analysis methods, are described in more detail by Pirzkal et al. (2004).

One of the primary scientific goals of GRAPES is to study the luminosity function of Lyman break galaxies (LBGs) using spectroscopically confirmed samples at unprecedented sensitivity, and thereby to constrain the faint-end luminosity function slope. We have begun this effort with a targeted look at photometrically selected Lyman break candidates, using both *i*-dropout galaxies from the UDF (Malhotra et al. 2005) and *V*-dropout galaxies, which we have identified (J. E. Rhoads et al. 2005, in preparation) by following the selection criteria outlined by Giavalisco et al. (2004b) in both the GOODS version 1.0 survey data (Giavalisco et al. 2004a) and the UDF. (We refer to ACS and NICMOS filters by names of roughly corresponding ground-based filters: F435W as *B*, F606W as *V*, F775W as *i*, F850LP as *z*, F110W as *J*, and F160W as *H*.) Most of the confirmed Lyman break objects are spatially compact, with sizes ($<0\farcs5$) and morphologies typical for the LBG population (e.g., Ferguson et al. 2004). In this paper we describe the most prominent exception to this pattern we have encountered to date, a *V*-dropout object (designated UDF 5225) that is exceptional in its size, morphology, and spectroscopic properties.

Throughout this paper we use the current concordance cosmology ($H_0 = 71$ km s^{-1} Mpc^{-1}, $\Omega_M = 0.27$, $\Omega_{\rm total} = 1$; see Spergel et al. 2003). Magnitudes are given on the AB magnitude system, so that magnitude zero corresponds to a flux density $f_\nu = 3.6$ kJy $= 3.6 \times 10^{-20}$ ergs cm^{-2} s^{-1} Hz^{-1}. We present the observations in § 2, compare them to various physical models for UDF 5225 in § 3, and summarize our conclusions in § 4.

2. OBSERVATIONAL PROPERTIES OF UDF 5225

UDF 5225 has two morphological components (see Fig. 1): a compact "core," which is barely resolved in the ACS data (with FWHM $\approx 0\farcs12$ in the UDF *z* filter image, which has a point-spread function [PSF] with FWHM $\approx 0\farcs10$) and an extended "plume" with size $\sim 1\farcs0 \times 0\farcs3$. There are three distinct condensations or "knots" within the plume. The core is located at $\alpha = 3^{\rm h}32^{\rm m}33\fs269$, $\delta = -27°47'25\farcs02$ (J2000.0), and the brightest knot in the plume ("K2" in Fig. 1) is at $\alpha = 3^{\rm h}32^{\rm m}33\fs243$, $\delta = -27°47'24\farcs48$. The optical and near-IR colors of the object (discussed below) identify it as a Lyman break object, with an

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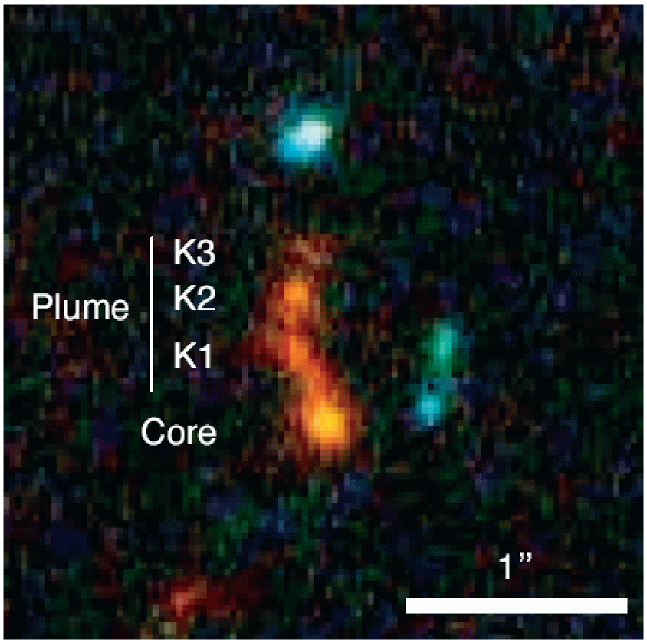

FIG. 1.—Color composite image of UDF 5225 from the Hubble Ultra Deep Field data. The elongated red source in the center is UDF 5225. We have labeled the "core" component at the bottom and the "plume" extending toward the top of the image. We also label the three knots in the plume as "K1," "K2," and "K3." The length of the plume is nearly 1″. Blue-colored objects nearby are unrelated foreground sources. Red represents the z filter, green represents an average of V and i, and blue represents the B filter. Based on the color composite UDF image by Z. G. Levay.

intrinsically blue spectrum suppressed by the intergalactic medium at V band and bluer wavelengths.

The size is unusual, relative to $z \approx 5$ LBGs selected photometrically from the GOODS data (Ferguson et al. 2004), which show a broad peak between 0.″1 and 0.″5 (comparable to the minor axis size of UDF 5225) and no galaxies as large as 1″ (the major axis size of UDF 5225). UDF 5225 is not in the Ferguson et al. sample, being slightly fainter than their flux limit.

The two-dimensional ACS grism spectra of UDF 5225 are shown in Figure 2. They detect UDF 5225 significantly in each of the five epochs analyzed (see Pirzkal et al. 2004; see also Riess et al. 2004 for more detail on epoch 0). Our strategy of using many roll angles results in a clean separation of the core and plume spectra for epochs 0–2 (P.A. = 117°, 126°, and 134°, where "P.A." refers to the position angle of the *Hubble Space Telescope*'s V3 axis), while the spectra from the two components are superposed in epochs 3 and 4 (P.A. = 217° and 231°). The spectrum from the northwestern tip of the plume is contaminated by the spectrum of an unrelated, brighter object in the P.A. = 134° data, but otherwise the UDF 5225 spectra are free of significant overlap.

Where the plume's spectrum can be examined independently of other sources, including the core (i.e., epochs 0–2 for part of the plume, and epochs 0–1 for the entire plume), it is dominated by a single strong emission line at ≈7800 Å. Because this line falls in the i-filter bandpass, and the plume is detected in both i and z images, we know that there must also be weak continuum emission from the plume on the red side of the line. The core shows both a break and a line at the same wavelength. When both core and plume component spectra are superposed (epochs 3–4), their combined line and continuum flux results in a stronger

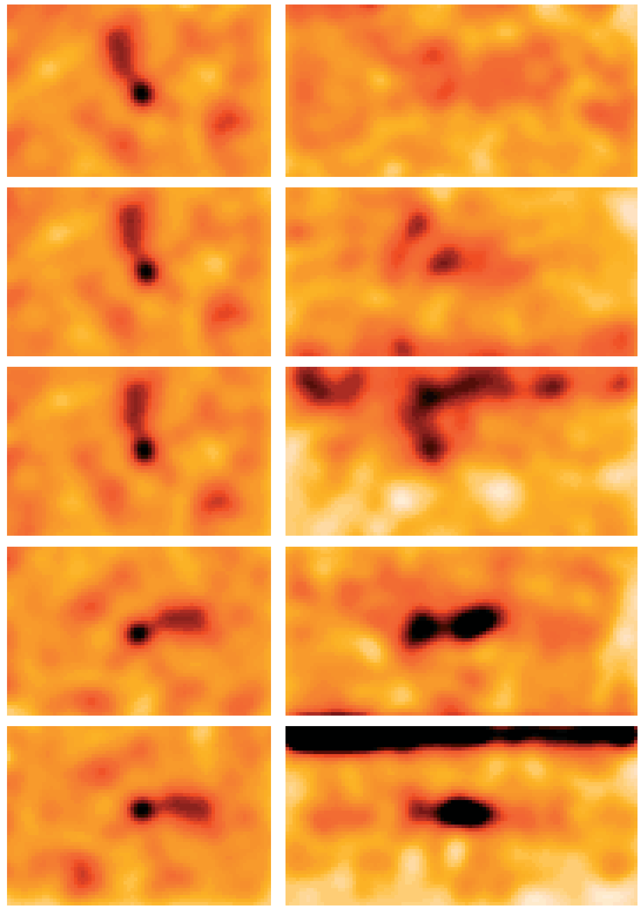

FIG. 2.—GOODS ver. 1.0 survey direct image of UDF 5225 in the z (F850LP) filter (*left panels*), together with the 2D GRAPES spectra (*right panels*) at each of five roll angles. From top to bottom, the angles shown are P.A. 117°, 126°, 134°, 217°, and 231°. The direct image is the same in all rows but is rotated to match the roll angle of each two-dimensional grism spectrum cutout. All images have been smoothed with a Gaussian filter matched to the angular size of the plume component (0.″3 FWHM) for maximum clarity. The upper edge of the grism spectrum in the third row shows contamination by an unrelated source elsewhere in the image. The Lyα emission from both plume and core is most clearly visible in the second and third rows; the first row is at a similar roll angle but is shallower. In the fourth and fifth rows, the line emission from the plume falls atop continuum emission from the core, resulting in a higher surface brightness in the dispersed image.

spectroscopic detection. We identify the line and break with Lyα, based on their wavelength coincidence in the spectrum of the core and on the B-band nondetection and very weak V-band flux of the source. This then implies a redshift $z \approx 5.42$, with an estimated uncertainty $\delta z \approx 0.07$. The object is near the upper end of the redshift range for V dropouts (and approaches the redshift range of i dropouts).

We measured the broadband optical magnitudes of the core and plume components using the UDF images. We defined apertures to match the morphology of the core and plume components. These apertures follow isophotes in a version of the UDF i-band image smoothed with a 0.″14 FWHM Gaussian kernel, except at the boundary between the two components. There is no deep minimum in surface brightness separating the core from the plume. We find for the core $i = 27.94 \pm 0.017$, $i - z = 0.51 \pm 0.025$, and $V - i = 2.3 \pm 0.12$ mag, while for the plume we obtain $i = 27.39 \pm 0.023$ mag, $i - z = 0.45 \pm 0.034$ mag, and $V - i = 3.3 \pm 0.45$ mag. Comparing our i-band flux with the flux in the UDF catalog from the Space Telescope Science Institute (STScI), we find that the masks contain about half of the overall flux of the source, with the remaining flux in lower surface brightness regions that we did not use for our color measurements. We did not attempt to measure the colors of the knots within the plume individually, but inspection of Figure 1 shows that they are consistent with the overall colors of the plume. Comparing the colors of the main components, we see that the core is slightly redder in $i - z$ and considerably bluer in $V - i$, but the significance of both statements is low: about 1.5 σ for $i - z$, and 3 σ for $V - i$ (note that we calculated the significance of the $V - i$ color difference directly from flux ratios, rather than from magnitudes). The $V - i$ colors are consistent with transmission through the Lyα forest of photons emitted at 912 Å $< \lambda_{\rm rest} <$ 1215 Å. For a flat ($f_\nu \approx$ constant) continuum, we would expect the Lyα forest to attenuate the V-band flux by a factor of 14 for a source at redshift $z = 5.4$, based on the formalism of Madau (1995).

To eliminate any possibility that UDF 5225 is simply a faint, intrinsically red galaxy at a lower redshift, we also examined the near-IR colors of the object, using NICMOS images of the UDF (PI: R. Thompson). We find a blue color ($z - J = 0.04$ and $J - H = -0.27$). The NICMOS measurements were performed using an elliptical aperture large enough to encompass the entire object (size $\approx 1''.0 \times 0''.25$). We did not attempt separate IR measurements of core and plume colors, given the larger pixel size, PSF size, and lower sensitivity of the UDF NICMOS data. The observed NIR colors support the identification of UDF 5225 as a Lyman break object with an intrinsically blue spectrum truncated below Lyα by the intergalactic medium.

Because UDF 5225 is both faint and extended, it is near the practical detection limit of the GRAPES data. We therefore combine the UDF imaging data, the NICMOS UDF observations, and the GRAPES redshift to estimate the line flux and equivalent width by fitting the spectral energy distribution (SED). We model the intrinsic spectrum as a power-law continuum plus an unresolved Lyα emission line, modifying both by the Lyα forest transmission calculated under the model by Madau (1995). The $z - J$ and $J - H$ colors are unaffected by Lyα emission and Lyα forest absorption, so we use them to constrain the intrinsic spectral slope to $\alpha \approx -2.4 \pm 0.3$, where $f_\lambda \propto \lambda^\alpha$. With the slope fixed, the $i - z$ and $V - i$ colors are determined by the line flux and the redshift (which determines how strongly Lyα forest absorption affects broadband fluxes). For $z = 5.42 \pm 0.07$, we find a rest-frame equivalent width of 70 ± 30 Å and an observed line flux of $(2.2 \pm 0.8) \times 10^{-17}$ ergs cm^{-2} s^{-1}. The range in line flux and equivalent width is primarily determined by the range of acceptable redshifts. Changing the continuum slope within its plausible range has a rather smaller effect on the line flux needed to match the $i - z$ color. The observed line flux corresponds to an approximate surface brightness of 7×10^{-17} ergs cm^{-2} s^{-1} arcsec^{-2}.

To test whether the Lyα emission in UDF 5225 could be powered by an active galactic nucleus (AGN), we examined the UDF direct images from multiple epochs for variability. We stacked the UDF i- and z-band data into eight epochs of approximately equal exposure time. We also stacked archival z-band imaging from *HST* program 9352, which is shallower than 1/8 of the UDF data but gives a longer time baseline ($\sim$1 yr). Subtracting the mean of the UDF stacks from each individual epoch shows no significant residuals at the location of UDF 5225, leading us to conclude that the source is not significantly variable in the UDF data, with an upper limit to flux variations of $\lesssim$10%. Unfortunately, at $z \approx 5.4$, any C IV line lies beyond the wavelength coverage of the grism (as do all redder AGN lines), while the N V line is not separable from the Lyα line at the resolution of the grism. UDF 5225 is not detected in X-rays, based on the 1.0 Ms *Chandra* Deep Field South catalog (Giacconi et al. 2002; Alexander et al. 2003), although given its high redshift, this does not strongly exclude an AGN; only one AGN at $z > 5$ has so far been discovered in the two *Chandra* deep fields (Barger et al. 2002), and an X-ray detection would only be expected for a rest-frame hard-band luminosity $>1.8 \times 10^{43}$ ergs s^{-1}. Higher resolution optical spectra of UDF 5225 could convincingly determine whether it harbors an AGN by measuring the velocity width of the Lyα emission.

3. MODELS FOR UDF 5225

What is the nature of the Lyα plume in UDF 5225? Both the line luminosity and the equivalent width are generally similar to those seen in narrowband-selected Lyα samples (e.g., Rhoads et al. 2000; Malhotra & Rhoads 2002; Ouchi et al. 2003; Hu et al. 2004). The morphology is reminiscent of radio galaxies (e.g., Windhorst et al. 1998), quasar jets, the "Lyα blobs" that have been observed at $z \sim 3$ (e.g., Steidel et al. 2000), the Lyα emitting host galaxy of GRB 000926 (Fynbo et al. 2002; Castro et al. 2003), and some other high-redshift galaxies (Pascarelle et al. 1996; Bunker et al. 2000; Keel et al. 1999).

We can consider several possibilities: a recombination nebula powered by in situ star formation, possibly triggered by a galactic merger; light from the core component scattered by either electrons or dust; or a recombination nebula powered by the core.

In situ star formation.—Star formation would provide a local source of ionizing photons within the plume. It also produces lower energy photons that would dominate the rest-UV continuum redward of Lyα. The resulting continuum slope is the bluest among the models considered here. The rest-frame Lyα equivalent width for star formation should be $\lesssim$240 Å, based on stellar population models at solar metallicity (Charlot & Fall 1993). While observations of Lyα galaxies at $z \approx 4.5$ often show larger values (Malhotra & Rhoads 2002), the presence of stars in situ will always reduce the equivalent width relative to recombination models in which the ionizing photon source is distant. Star formation is consistent with essentially any morphology. A conversion factor of 1 $M_\odot$ yr^{-1} = 10^{42} ergs s^{-1} is widely used for high-redshift Lyα emission, and would imply star formation at $\gtrsim 7\ M_\odot$ yr^{-1} in the plume, subject to the standard (but untested) assumptions that the star formation follows a Kennicutt (1983) initial mass function (IMF) and that case B recombination is valid. If we base our estimate instead on the rest-frame UV continuum emission at 1425 Å, as measured by the z-band image, we find a star formation rate of $\approx 4\ M_\odot$ yr^{-1} for the plume (plus another 2.5 $M_\odot$ yr^{-1} in the core, assuming the core light is not dominated by an active nucleus). The conversion factors for both continuum and line light are substantially uncertain, because of necessary but uncertain assumptions about the IMF and about the effects of gas and dust on Lyα radiative transfer. Thus, this constitutes remarkably good agreement.

Scattered light.—If UV radiation from the core encounters a sufficiently dense scattering medium, a detectable scattering cone could be produced. This is the least plausible explanation for the UDF 5225 plume because the core luminosity would have to be very large to power electron scattering, while dust scattering would be unlikely to produce a large Lyα equivalent width and a blue continuum color.

We estimate the mass of scattering material required, using the approximation that the plume is a cone with length 6 kpc and base diameter ~2 kpc. The corresponding volume (in physical, not comoving, units) is 2×10^{65} cm^3. We estimate the mass for a scattering optical depth τ_e from the core to the end of the cone. Then, for electron scattering (with $\sigma_T = 1.6\times10^{-24}$ cm^2) we find a number density of $n_e \approx 25\tau_e$ and a corresponding mass of $\sim5\times10^9\tau_e\,M_\odot$ in the cone. This gas would emit copious Lyα radiation. Indeed, to avoid producing more than the observed Lyα luminosity would require that $\tau_e \lesssim 0.025$. Clumping of the scattering gas would be required to reproduce the observed knots and the 30° bend in the plume. This clumping would further enhance recombinations and further reduce the maximum τ_e for electron scattering to dominate the plume emission.

Such low optical depths imply that electron scattering is a very inefficient way of producing the Lyα nebulosity because scattered light will be suppressed by a factor τ_e. The scattering region must then be illuminated at a much higher intensity than one would naively infer from the observed core flux. Consider a simple toy model in which the central source has two emission components, one with a ~30° opening angle that powers the observed plume, and one isotropic that powers the observed core and that we allow to be attenuated by optical depth $\tau_{\rm abs}$ of absorption. To reproduce the observed plume to core flux ratio, the collimated component would then need to contain a fraction $\sim[1 + 0.6\tau_e \exp(\tau_{\rm abs})]^{-1}$, which becomes $\sim1 - 0.6\tau_e \gtrsim 98\%$ in the limit in which $\tau_{\rm abs} \lesssim 1$. This would correspond to a total source UV luminosity $\nu L_\nu \gtrsim 3\times10^{45}$ ergs s^{-1} (measured in the z-band, which is $\lambda_{\rm rest} \approx 1410$ Å); i.e., $7\times10^{11}\ L_\odot$ or an angle-averaged absolute AB magnitude of -23.7. This luminosity would increase if either the assumed τ_e or the degree of collimation were reduced. Such a model would likely require an AGN in the core because starlight cannot be tightly collimated, thus increasing the luminosity requirement by another factor of $\gtrsim$10, while also requiring $\tau_{\rm abs} \gtrsim 2$ on the line of sight to the core. The mass of ionized hydrogen required in an electron scattering scenario would be modest, $\lesssim10^8\ M_\odot$.

Dust scattering in an ionized medium could work, as long as the optical depth is suitably small so that (1) there is no significant reddening of the scattered continuum light, and (2) Lyα radiation is not selectively absorbed relative to the continuum. Condition (1) requires $\tau \lesssim 0.1$ at $\lambda_{\rm rest} \approx 1300$ Å; and similarly, condition (2) requires $\tau \lesssim 0.05$ at $\lambda_{\rm rest} \approx 1216$ Å to avoid attenuation of Lyα by more than a factor of 2 (Panagia & Ranieri 1973a, 1973b). The associated total mass of gas and dust would be $M_{\rm plume} \approx 10^7\tau_{\rm dust}(1216\ \text{Å})\ M_\odot$, assuming a dust-to-gas mass ratio of 0.01. Inserting $\tau_{\rm dust} < 0.1$ gives $M_{\rm plume} \sim 10^6\ M_\odot$. The requirement on the core luminosity can be derived exactly as in the case of electron scattering, but now with larger scattering opacity, so the final constraint becomes $\nu L_\nu \gtrsim 3\times10^{44}$ ergs s^{-1}.

An additional concern with scattering models is that the intensity of scattered light should decrease away from the AGN (falling off as r^{-2} in the simplest case, although projection effects and anisotropic quasar emission could modify this). Yet the surface brightness of the plume is constant to within factors of 2 over a factor of ~8 in distance from the core, which would require the column density to increase with distance as $\sim r^2$.

Recombination powered by core light.—Objects such as "Lyα blobs" (e.g., Steidel et al. 2000) and some radio galaxies have extensive Lyα nebulae (up to 100 kpc in size) that are likely powered by AGN emission. We now consider whether UDF 5225 could be a physically similar object on a smaller scale.

Such a model is similar to the electron scattering model but with higher densities, in which recombinations become more important than electron scattering. In this case the mass of ionized hydrogen involved would be $\gtrsim10^8\ M_\odot$. The core luminosity could be much lower in this case: for an ionization-bounded nebula, it need only be about twice the measured Lyα luminosity, i.e., $>2\times10^{43}$ ergs s^{-1} in ionizing radiation, although it could be much larger if the radiation is largely isotropic and the morphology of the plume is set by the location of substantial gas.

However, in this case, the continuum emission from the plume would be pure nebular emission, with components from the two-photon process, bound-free emission, and free-free emission. The expected equivalent width of the line would then be >1000 Å (rest frame) and the z-band continuum should be much weaker than we see. While dust attenuation of the Lyα might help, the model would have to be fairly contrived to simultaneously fit the Lyα flux, continuum flux, equivalent width, and color in the plume, and we therefore disfavor this model also. The only countervailing argument comes from the V-band flux, which should be absent in a two-photon continuum and is indeed rather weaker in the plume than in the core. However, none of the V-band detections is strong, so it is not clear if the difference in $V - i$ and $V - z$ colors between the two components is significant.

A merger scenario.—Consider the possibility that UDF 5225 is a major merger in progress at $z \approx 5.4$. The nuclei of the two interacting galaxies would then presumably be the "core" component we have discussed, plus the brightest "knot" in the plume, which lies 0.″63 away. Quantitative morphological tests based on the asymmetry parameter A (e.g., Conselice et al. 2003) are consistent with this scenario, based on an analysis of GRAPES object morphologies now in progress (N. Pirzkal et al. 2005, in preparation). If we measure asymmetry relative to the center of light for UDF 5225 (i.e., almost half-way from the core to the end of the plume), we find $A(z) = 0.34 \pm 0.09$ and $A(i) = 0.16 \pm 0.09$ for the z and i filters. If we instead measure A, with the center placed in the core component, we get much higher numbers, $A(z) = 0.45 \pm 0.13$ and $A(i) = 0.43 \pm 0.13$. Mergers are typically found to have $A \gtrsim 0.35$ (Conselice et al. 2003). Further discussion of these parameters for the full i- and V-drop GRAPES samples will be presented in N. Pirzkal et al. (2005, in preparation).

The projected separation of the core and knot, ~4 kpc, would then imply a crossing time of the order of $40v_{100}$ Myr, where $v_{100} \sim 1$ is the relative velocity of the two components, in units of 100 km s^{-1}. Multiplying this by the star formation rates inferred in § 3 implies formation of some few $10^8\ M_\odot$ of stars in the course of the interaction.

The star formation rate per unit area, based conservatively on the UV-derived SFR for the plume, is $\sim0.4\ M_\odot$ yr^{-1} kpc^{-2}. Comparing with the global Schmidt law for star formation, we would infer a gas mass surface density of $\sim800\ M_\odot$ pc^{-2}, for a total gas mass of order $7\times10^9\ M_\odot$. This number implies a gas consumption timescale of $\sim10t_{\rm dyn} \sim 600$ Myr, although if star formation is proceeding at an atypically high rate (driven by interaction), the gas reservoir could be smaller.

4. DISCUSSION

We have examined several possible scenarios for the observed properties of the galaxy UDF 5225, a very faint and high-redshift object with a core-plume morphology and prominent Lyα emission. We conclude that the Lyα emission is most likely powered by in situ star formation throughout the object. Present evidence neither requires nor rules out the presence of an AGN in the core component. Follow-up spectroscopy using higher spectral resolution and/or coverage into the near-IR would provide new information that could settle the AGN question. Tidally triggered star formation in a merging galaxy pair seems to describe the galaxy well. As such, it may be a particularly spectacular example of the broad class of star-forming Lyman break galaxies that dominate the galaxy population observed in the Hubble Ultra Deep Field and other very sensitive high-redshift galaxy surveys.

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Note added in proof.—H. Spinrad and collaborators have recently obtained a follow-up spectrum of UDF 5225 using the DEIMOS spectrograph on the Keck II telescope. They confirm the presence of a Lyα line and measure a redshift $z = 5.480$. Their results are in preparation for publication as Stern et al. (2005).