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EXTENDED LYMAN-α EMISSION IN 3C 326.1: A 100 KILOPARSEC CLOUD OF IONIZED GAS AT A REDSHIFT OF 1.82[1]

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ABSTRACT

We report the discovery of a large cloud of ionized gas associated with the high-redshift radio source 3C 326.1 New radio-frequency images made at 4.9 GHz and 15 GHz with the Very Large Array show the radio source to be a small double (~ 7″) without a detectable core at the level of ~ 0.5 mJy. Long-slit spectrograms and Lyα imaging reveal a ~ 100 kpc diameter cloud of ionized gas with a redshift of 1.825 encompassing the radio source. Deep broad-band images show two faint ($V \approx 23.5$–24.5) blue objects located on the periphery of the cloud, as well as some very faint ($V \approx 25$–26) extremely blue diffuse objects roughly coincident with the brightest regions of the cloud. Long-slit CCD spectra suggest that the Lyα emission from the cloud has a large intrinsic width (FWHM ≈ 1000 km s^{-1}). Spectra taken in the red show weak extended emission from C II] and C III], but C IV emission has not been detected. The large equivalent width of Lyα and the relative strengths of the carbon lines are consistent with H II region–type photoionization. We tentatively propose that 3C 326.1 is a young and/or forming galaxy.

Subject headings: galaxies: formation — radio sources: galaxies

I. INTRODUCTION

Strong narrow Lyα emission is conceptually a nearly ideal tracer for detecting distant galaxies and perhaps even protogalaxies. Lyα searches for protogalaxies in the redshift range 4–6 have been carried out by a number of groups (see the review by Koo 1986). All of these searches reported to date have failed to detect any convincing candidates. Recently, however, Lyα searches for distant galaxies have had some limited success (e.g., Djorgovski *et al.* 1985; Spinrad *et al.* 1987). The observations reported here come from a program to locate distant radio galaxies by their strong narrow Lyα emission lines (cf. Spinrad *et al.* 1985). The object that we describe is the best candidate for a protogalaxy yet observed, and may provide needed encouragement for continuing Lyα searches for more protogalaxy candidates.

II. OBSERVATIONS AND REDUCTIONS

Throughout this paper we will refer to the various objects in the 3C 326.1 field by the designations given in Figure 1 (Plate L4). Object W is Wyndham's (1966) identification and is a foreground galaxy, M is a very red foreground star, A is a very blue object located on the northern periphery of the Lyα cloud, and B is a moderately blue object located on the eastern side of the Lyα cloud.

Deep broad-band images of the 3C 326.1 field were made on the Kitt Peak National Observatory (KPNO) Mayall 4 m telescope using the prime focus TI 800 × 800 CCD direct camera (De Veny 1983) on 1986 April 5. Exposures were made in R (2 × 800 s), V (1000 s), and B (2 × 600 s). The seeing had a full width at half-maximum (FWHM) of ~ 1″ throughout the time of the observations. The separate images for each filter were shifted into registration and combined. A stack of all of the images was also constructed from the B, V, and R images (Fig. 1*a*). Broad-band g and r images of the field taken with the Hale 5 m telescope were kindly provided by R. Windhorst and D. C. Koo.

High-resolution radio observations of 3C 326.1 were made with the Very Large Array (Thompson *et al.* 1980) in the A configuration on 1986 April 1 at 6 cm and 2 cm. The observed wavelengths were 6.20 cm, 6.14 cm, 2.03 cm, and 2.01 cm, each with bandwidths of 50 MHz. The resolutions for the 6 and 2 cm observations were 0″.39 and 0″.13, respectively. The source was observed for 60 minutes at 6 cm and 70 minutes at 2 cm, with observations of phase calibrators interleaved throughout. The reductions and analysis were carried out using standard techniques (see, e.g., van Breugel *et al.* 1985).

Spectroscopy of A in the near-ultraviolet obtained with the Multiple Mirror Telescope (MMT) through a 2″ × 4″ aper-

[1]Based in part on observations performed at Lick Observatory, University of California, the Kitt Peak National Observatory (NOAO) and the Multiple Mirror Observatory, a joint facility of the Smithsonian Institution and the University of Arizona.

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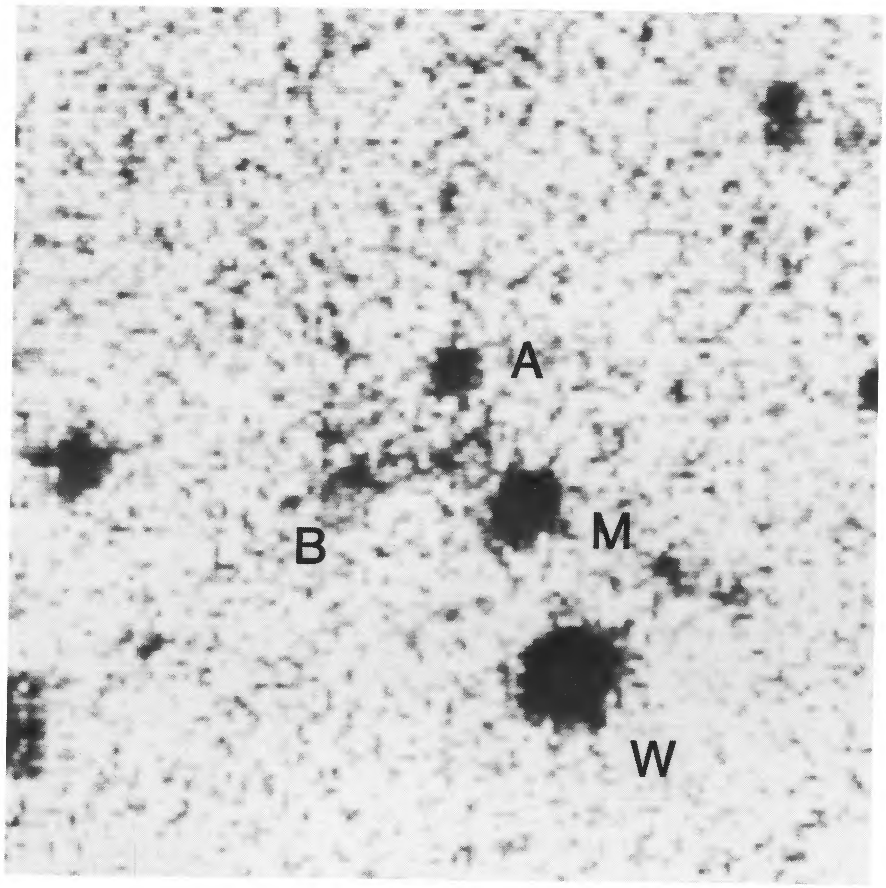

FIG. 1*a*

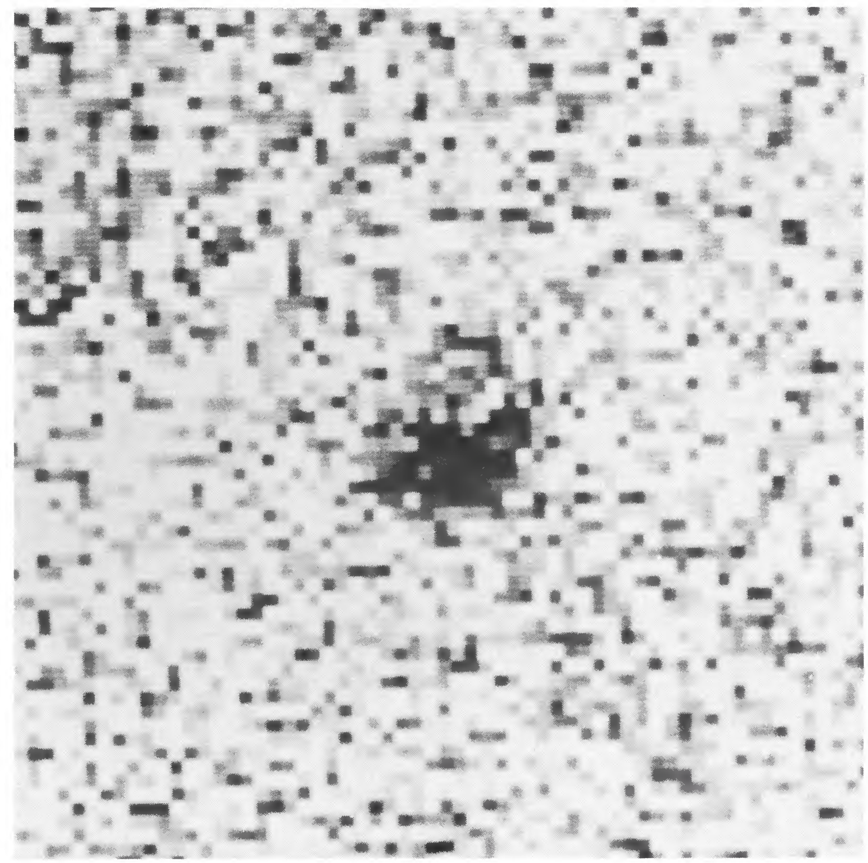

FIG. 1*b*

FIG. 1.—(*a*) A composite of our broad-band *BVR* stack of the 3C 326.1 field obtained with the Kitt Peak Mayall 4 m PFCCD. (*b*) Our Lyα interference filter image obtained with the Lick Shane 3 m Cassegrain CCD camera. Note that the stars make an undetectable contribution in this image. The size of the images is 35″ for each and the images are in registration. The objects discussed in the text are labeled.

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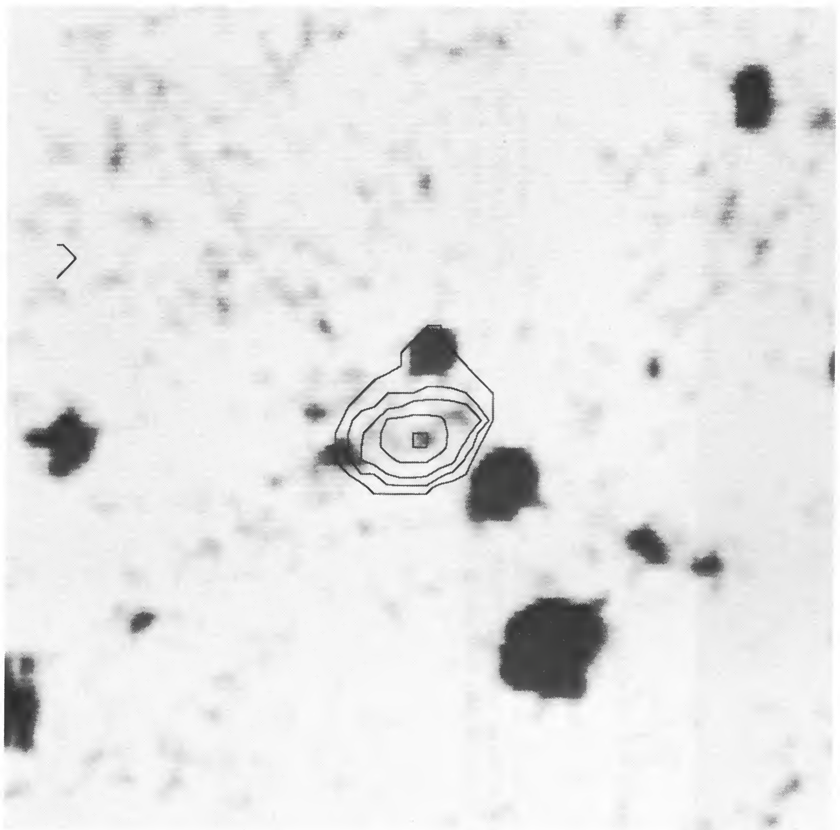

FIG. 5*a*

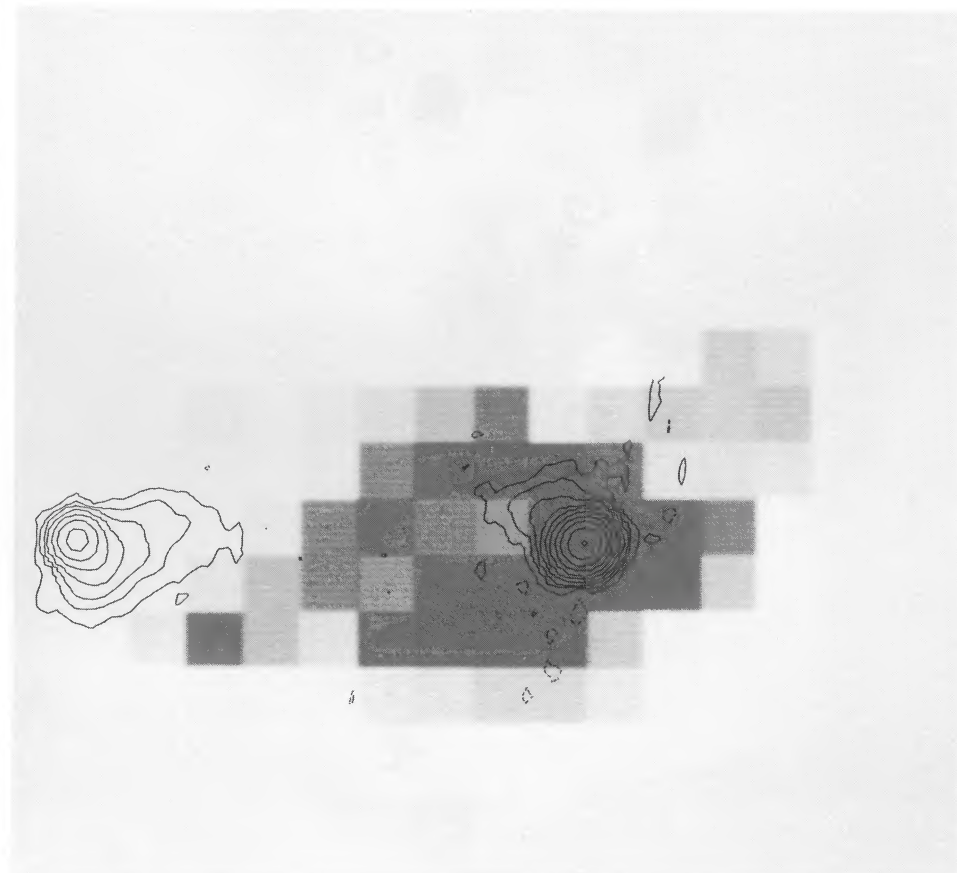

FIG. 5*b*

FIG. 5.—(*a*) An overlay of our broad-band stack and a contour representation of our Lyα image. (*b*) An overlay of our Lyα image and a contour representation of our 6 cm total intensity map.

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ture on 1986 March 9 resulted in the detection of an emission line at 3433 Å. This was confirmed by subsequent observations with the MMT on 1986 May 4. MMT observations of B resulted in the detection of the same emission line, in this case at ~ 3450 Å. We tentatively identified these emission lines as Lyα at a redshift of ~ 1.82. The radio observations described above show that object A could not be the correct identification of the radio source; B is, however, a viable but highly uncertain identification (see the discussion below and Fig. 5). Long-slit spectra in the near-ultraviolet were obtained at Lick Observatory with the Cassegrain Schmidt Spectrograph and a backcharged TI CCD on the Shane 3 m telescope. The first observations were made with the slit in position angle (PA) 133° and were placed so as to cover both objects A and B. Three integrations of 1 hr each and one integration of 30 minutes duration were made on 1986 June 6 and 7. The observations were combined by using stars along the slit as reference points for registration of the various frames. These long-slit spectra confirmed the presence of emission lines in A and B and in the region between them. Long-slit UV spectra were obtained with the same instrument on 1986 July 7, but with the slit at PA 270°, placed so as to cover the region ~ 3″ south of A. The integration time for this spectrum was 1 hr. The PA 133° spectrogram shows emission stretching from A to B and reaching maximum intensity in the region *between* A and B. The PA 270° spectrogram shows emission extending ~ 8″ along the slit. The precise redshift determined from these spectra is 1.825 ± 0.005.

Two long-slit spectra of 1 hr exposure each were obtained with the KPNO Cryogenic Camera (De Veny 1983) in the visual-red region (~ 5000 to ~ 8000 Å) on 1986 May 10. The slit was aligned at PA 133° and oriented as described above for the UV long-slit observations. The spectra revealed weak emission lines at 5383 Å and 6556 Å. We identify these features as C III] λ1909 and C II] λ2325 at a redshift of 1.82. The detection of these lines at the reported wavelengths confirms our identification of the extended near-UV line as Lyα. Careful examination of these spectrograms shows that the carbon emission lines are extended and peak between A and B, as is the case for Lyα.

The final step was interference filter imaging in the light of Lyα. An interference filter with a central wavelength of 3440 Å and a FWHM ~ 90 Å was used with the Cassegrain Schmidt CCD Camera on the Lick Observatory 3 m telescope. Four 1 hr integrations and one 30 minute integration were made on 1986 July 7 and 8 under photometric conditions with 1″.5 seeing. Short integrations made with a broadband filter (λ_c = 3500 Å) after each interference filter image were used to determine the position of the Lyα cloud relative to the other objects in the field. Observations of standard stars from Stone (1977) were used to flux-calibrate the Lyα images.

III. RESULTS

Throughout the following discussion we will adopt the set of cosmological parameters: $H_0 = 50$ km s^{-1} Mpc^{-1}, $q_0 = 0$, and $\Lambda_0 = 0$. This gives a size scale of ~ 12 kpc per arcsecond at a redshift of 1.825. The 6 cm total intensity map is shown in Figure 2. Note that the observed wavelengths, 6 cm and 2 cm, correspond to emitted wavelengths of 2.2 cm and 7 mm, respectively. The angular extent of the radio source is 6″.7, corresponding to a projected linear size of 85 kpc. The total power at 4.9 GHz is 2.5 × 10^{28} W Hz^{-1}. Neither our 6 cm nor our 2 cm observations resulted in the detection of a core source, our 3 σ upper limit being ~ 0.5 mJy at either wavelength. The two lobes show a large brightness contrast and significant differences in spectral index, the western lobe being 4–5 times brighter than the east lobe and having a flatter (but still steep) radio spectrum. The spectral indices of the east and west lobes are $\alpha^{2\,\mathrm{cm}}_{7\,\mathrm{mm}} = -1.43$ and -1.08, respectively. We derive a surprisingly low polarization at λ_{rest} = 7 mm of ~ 7.5% at the peak intensity in both lobes.

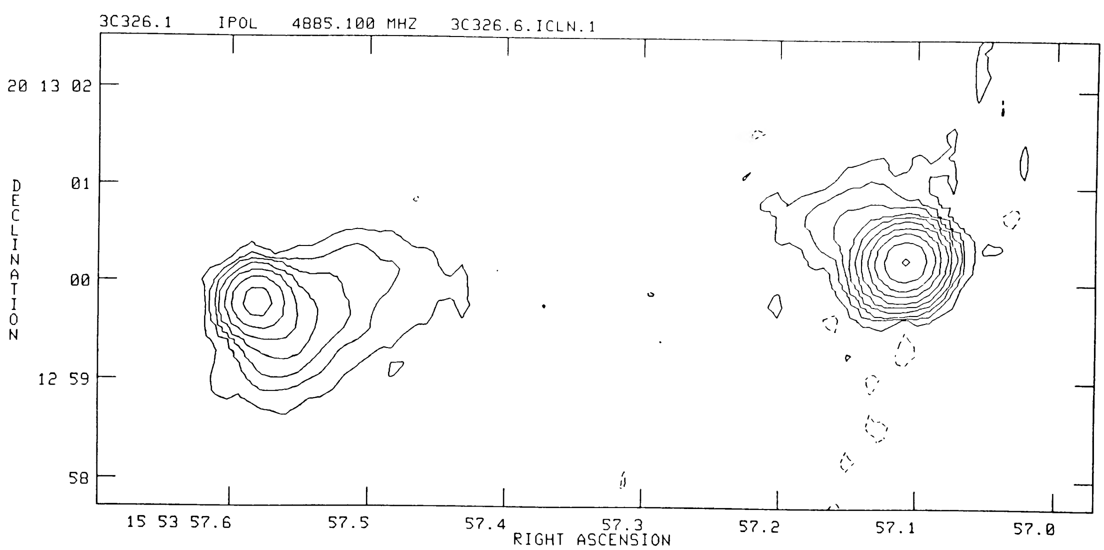

FIG. 2.—A 6 cm total intensity map of 3C 326.1 made with the VLA in the A configuration. The contour levels are −3, 3, 10, 20, 40, 80, 160, 320, 640, 1280, and 2560 × 0.15 mJy per beam.

This could mean that significant depolarization has occurred at this wavelength, suggesting the presence of a dense ionized medium *within* the radio-emitting plasma, perhaps entrained in the turbulent boundary layers as the hot spots propagate through the Lyα cloud. Future observations with matched beams are required to investigate the significance of the inferred depolarization. In its radio properties 3C 326.1 resembles the prototypical powerful radio galaxy Cygnus A in projected size, power, spectral index, and polarization properties (Dreher, Carilli, and Perley 1987).

One-dimensional extractions from our UV slit spectra are shown in Figure 3. The spectra show the strong Lyα emission from the gas cloud. After correcting for the instrumental resolution (~ 21 Å) we derive FWHM for the PA 133° and PA 90° spectrograms of 1200 ± 350 km s^{-1} and 900 ± 400 km s^{-1}, respectively. The PA 133° spectrogram shows a velocity gradient of ~ ± 500 km s^{-1} over 150 kpc, consistent with the MMT aperture spectra; unfortunately, our long-slit spectra in the red do not have the signal-to-noise ratio necessary to confirm this. Our PA 90° spectrogram shows no detectable velocity gradient. We derive a lower limit to the observed Lyα equivalent width of 1000 Å from our long slit UV spectra. This limit corresponds to an equivalent width of ~ 350 Å in the rest frame, similar to Lyα equivalent widths in other distant 3CR galaxies (Spinrad *et al.* 1985).

Figure 4 shows a one-dimensional extraction from our KPNO visual-red long-slit spectrogram, summed over the same region as the UV spectrum. The spectrum confirms our Lyα-based redshift of 1.825 and shows that the cloud has a nonprimeval composition. The width of C II] λ2325 derived from these spectra is ~ 200–400 km s^{-1}, but the uncertainty in this measurement is very large. The relative line strengths (for PA 133°) are C III] λ1909/Lyα = 0.05 ± 0.03 and C II] λ2325/Lyα = 0.04 ± 0.02. Our long-slit Lick UV spectra give an upper limit of C IV λ1549/Lyα < 0.02.

Figure 1*a* shows a stack of our *B*, *V*, and *R* direct images of the 3C 326.1 field, with a total integration time of 63 minutes. We have labeled the important objects in the field. The relatively bright object A, has an *R* magnitude of 23.5 and the faintest objects visible in the field have surface brightness of 27 mag per square arcsecond. Photometry obtained from Windhorst and Koo's 5 m CCD images indicate that object A has a $g - r$ color of ~ 0.2 and that the faint object near the center of the Lyα cloud is *extremely* blue, with $g - r < 0$. Figure 1*b* shows our stacked Lyα image with the same scale and orientation as the broad-band image. The Lyα emission cloud is roughly elliptically shaped with the long dimension being ~ 10″. The Lyα image is remarkably smooth, with no obvious strong central concentration of the emission-line gas. This lack of a central source in the line emission is also apparent in our long-slit data. The azimuthally averaged surface brightness profile of the Lyα image has a decline that is well fitted by a $r^{-1.3}$ power law.

The total flux detected from the Lyα cloud is 7×10^{-15} ergs cm^{-2} s^{-1}, corresponding to a monochromatic luminosity of 3.6×10^{44} ergs s^{-1} for the adopted cosmology. The total luminosity of the cloud is of the order 10^{45} ergs s^{-1}. This luminosity is large, but not uncommon for the extended

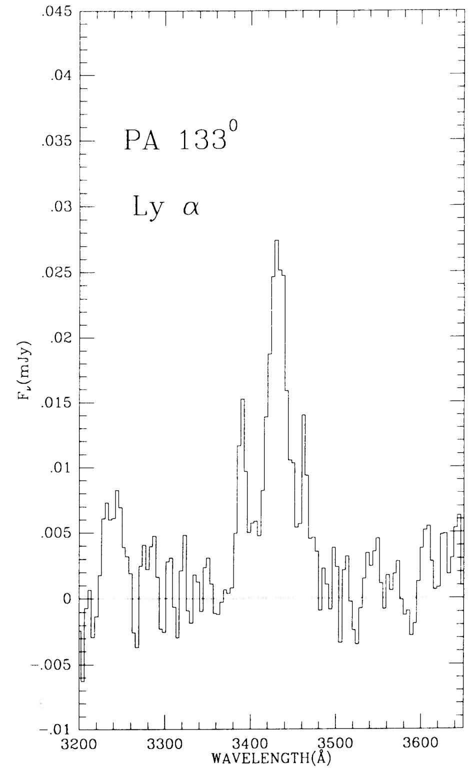

FIG. 3*a*

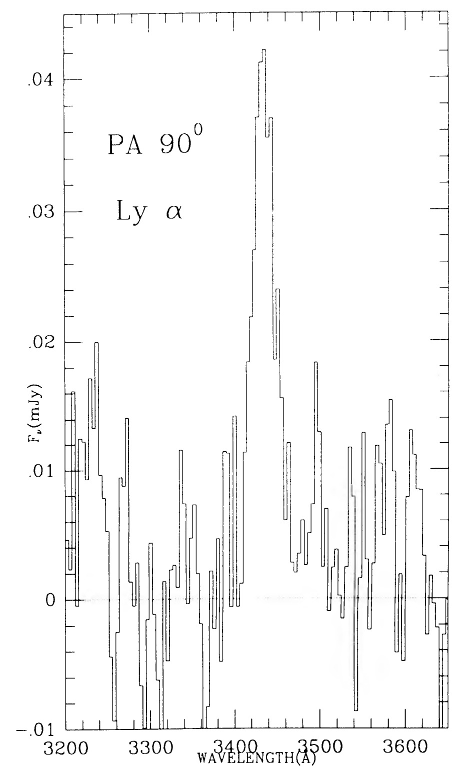

FIG. 3*b*

FIG. 3.—One-dimensional extractions from our Lick UV two-dimensional spectrograms. Fig. 3*a* is a sum over 10″ in position angle 133°. Fig. 3*b* is a sum over 5″ in position angle 90°. Only the region around Lyα is shown in each plot.

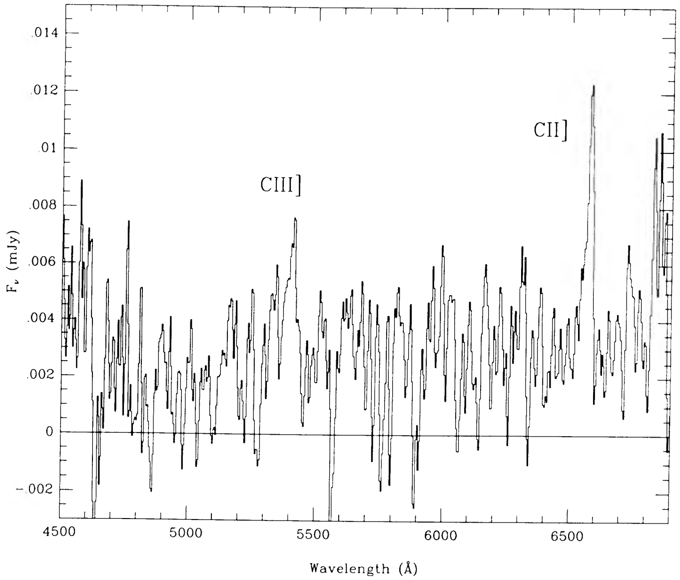

FIG. 4.—A one-dimensional extraction from our Kitt Peak Cryogenic Camera spectrogram of 3C 326.1. The spectrum is a sum over 10″ in position angle 133°. The lines of C II] λ2325 and C III λ1909 are marked. The continuum is primarily from the objects A and B.

nebulae around distant 3CR galaxies (Spinrad *et al.* 1985; Djorgovski *et al.* 1987*a*). Figure 5 (Plate L5) shows overlays of the continuum, Lyα, and 6 cm images. It is clear that our initial identification, A, and Wyndham's (1966) identification, W, are both incorrect. The faint object B, is ~ 2″ away from the center of the two lobes, which is ~ 25%–30% of the lobe spacing, so we consider it to be a possible but highly uncertain candidate for the source of the radio plasma. The broad-band images show faint condensations or "knots" at near the center of the Lyα cloud. The emission from C II] λ2325 and C III] λ1909 produce a peak surface brightness of ~ 28 mag per square arcsecond, roughly 1.5 mag fainter than the surface brightness that we observe in V in the knots. Thus we believe that these knots are continuum emission, presumably of a stellar origin. Figure 5 also shows that the emission-line gas cloud envelopes a large fraction of the radio source, and that the western lobe is in a region of higher surface brightness Lyα emission.

IV. DISCUSSION

We will attempt to estimate the physical properties of the 3C 326.1 system from the observations described above, and compare it to other distant extended Lyα objects. The first issue that we address is the source of ionization in the Lyα cloud. The large size of the cloud and the lack of any central condensation in the Lyα image both argue against photoionization by a central power-law continuum source (e.g, an obscured QSO). Large-scale nebulae have been observed surrounding a number of quasars at low redshifts by Stockton and MacKenty (1983, 1987) and by Hintzen and Romanishin (1986) at higher redshifts. 3C 326.1, however, is quite different from these objects in that there is no luminous galaxy or quasar apparent near the center of the cloud. The most compelling argument against the source of ionization being an obscured quasar is the lack of a flat spectrum core (or any core component for that matter) associated with the radio source.

We consider the possibility that the Lyα cloud is photoionized by far ultraviolet radiation (FUV) from young stars. The relative strengths of the C II], C III], and C IV (upper limit) are close to the values observed for the Orion Nebula by Torres-Peimbert, Peimbert, and Daltabuit (1980), and are consistent with the predictions for model H II regions with mean $T_{\rm eff}$ = 40,000 K and metal abundances of ~ 10%–20% solar (Stasinska 1982; G. Ferland, personal communication). From the O star models of Hummer and Mihalas (1970) we find that a 40,000 K O star with low surface gravity will produce a Lyα equivalent width of ~ 300 (assuming case B recombination), consistent with what is observed. Thus the spectroscopic data are consistent with photoionization by young stars, the large equivalent width of Lyα perhaps indicative of an IMF biased toward massive stars. Assuming that all Lyman-continuum photons are converted into Lyα photons (i.e., case B), we estimate that there are 10^{55} ionizing photons produced per second in the cloud. This flux of ionizing photons is ~ 50× that deduced for the central starburst of M82 by Rieke *et al.* (1980), suggesting a "burst strength" that is correspondingly large. We estimate the rate of formation of massive stars by assuming the case B recombination value for Lyα/Hα of 8.74 (Brocklehurst 1971) and employing the relation between $L_{\rm H\alpha}$ and the star-formation rate (SFR) given by Kennicutt (1983). From this we derive a formation rate for stars more massive than 10 $M_\odot$ of ~ 70 $M_\odot$ yr^{-1}, and a total SFR of ~ 500 $M_\odot$ yr^{-1} assuming a standard Salpeter IMF. The later SFR may be an overestimate since the Lyα equivalent width, suggests a nonstandard IMF, as discussed above. While the inferred SFR is quite large, the total area over which star formation is likely to be occurring is also quite large, so that the rate of star formation per unit of projected area is comparable to or less than that inferred for nearby IR-luminous starburst galaxies. The deduced star formation implies a supernova rate on the order of ~ 5 yr^{-1}, using a mean of the supernova rates for late-type galaxies given by Tammann (1982). Such a supernova rate may account for the observed large line widths, either through multiple scatterings of Lyα off slow moving shock fronts or through large-scale supernovae-driven outflows of the type seen in nearby starburst galaxies (McCarthy, Heckman, and van Breugel 1987; Heckman, Armus, and Miley 1987). The non-primeval composition of the gas could also be due to rapid enrichment of the gas by supernovae.

The total mass of the ionized gas in the Lyα cloud cannot be determined directly. We can, however, place an upper limit on the gas mass by again assuming that case B recombination applies and that the gas uniformly fills the cloud. This gives $n_e \approx 0.05$, implying a total mass of ionized gas of the order 10^{11} $M_\odot$. Small-scale clumping of the gas could reduce the required gas mass, however, by orders of magnitude. This upper limit and the star formation rate estimated above gives a lifetime for the starburst of ~ 10^8 yr, similar to that derived for nearby starbursts (e.g., Rieke *et al.* 1980). If the ionized gas is in the form of dense H II regions, the photon flux of 10^{55} s^{-1} ($\sim 10^6$ O stars), suggests a mass of ionized gas on the order of 10^7 $M_\odot$. The mass in stars and neutral gas is unknown.

The next issue that we address is that of the radio source. If 3C 326.1 is truly a protogalaxy then it has "learned" how to make a powerful nonthermal radio source before it has formed most of its stars! It is conceivable that the core of the system formed at an early epoch, $z \approx 5$–10, and that star formation was delayed until subsequent infall and capture of gas (Silk 1987). The intense burst of star formation that we infer in the Lyα cloud may have been triggered by the formation of the radio source, and in particular by the propagation of the radio hot spots through the gas.

Finally, we consider 3C 326.1 in relation to other distant extended Lyα objects. The companion galaxy to the quasar PKS 1614+051 observed by Djorgovski *et al.* (1985, 1987*b*) and Hu and Cowie (1987) differs from 3C 326.1 in that it clearly has an unresolved nucleus in the Lyα images and has a Lyα luminosity that is a factor of 10 fainter. Many distant radio galaxies have large regions of extended line emission (e.g., 3C 324, Spinrad and Djorgovski 1984*a*; 3C 267, Spinrad and Djorgovski 1984*b*; 3C 368, Djorgovski *et al.* 1987*a*). The major difference between 3C 326.1 and other 3CR radio galaxy nebulae is the lack of a central luminous galaxy associated with 3C 326.1. All other distant radio galaxies with large-scale nebulae have well developed central galaxies, and these often have nuclei with strong nuclear emission lines. The other 3CR galaxies with similar redshifts have strong high ionization lines (e.g., C IV and He II) indicating that stellar UV is not the dominant source of ionizing photons (Spinrad *et al.* 1985). Furthermore, the 3CR galaxies with $z \approx 1.8$ (that have good photometry) have continuum magnitudes that are 1.5–2 mag brighter than A, the brightest object associated with 3C 326.1 (Djorgovski, Spinrad, and Dickinson 1987). Thus support for 3C 326.1 being a protogalaxy comes not only from the gas, but also from the lack of a luminous stellar component of the type seen in other distant 3CR galaxies. 3C 326.1 may be an example of a 3C 368–like object in an earlier stage of development.

If 3C 326.1 is a protogalaxy, there may be important implications for our understanding of galaxy formation in general. The rather late epoch at which we observe 3C 326.1 to be forming ($z \approx 2$) suggests that galaxy formation may have occurred over a significantly extended epoch. The density of objects similar to 3C 326.1 on the sky is observationally unconstrained, since most Lyα protogalaxy searches have concentrated on the redshift range of ~ 4–6 (see the review by Koo 1986). A recent theoretical discussion of the expected number counts of objects of this type is given by Baron and White (1987). The advent of low-noise blue-sensitive CCDs will make searches for $z \approx 2$ Lyα objects more attractive. The strong Lyα emission seen in this and all other 3CR galaxies with redshifts large enough to put Lyα over the atmospheric ozone horizon, is direct evidence that young galaxies need not be shrouded in dust, as suggested by the UV observations of metal-poor dwarf galaxies by Hartmann, Huchra, and Geller (1984). However, if a starburst of duration $\sim 10^8$ yr is responsible for the Lyα emission, detection of similar objects by their Lyα emission will be difficult, as the Lyα bright phase will be short compared to the dynamical time scale for accumulation of substructure.

We conclude by noting that the observations described above provide additional evidence that the epoch of galaxy formation is quite extended, as indicated by observations of low-mass galaxies undergoing their initial bursts of star formation now (e.g., Kunth and Sargent 1986) and observations of large gas clouds that have yet to undergo a significant amount of star formation (e.g., Bothun *et al.* 1987).

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