DISCOVERY OF NINE Lyα EMITTERS AT REDSHIFT $z \approx 3.1$ USING NARROWBAND IMAGING AND VLT SPECTROSCOPY

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ABSTRACT

Narrowband imaging surveys aimed at detecting the faint emission from the 5007 Å [O III] line of intracluster planetary nebulae in Virgo also probe high-redshift $z \approx 3.1$ Lyα emitters. Here we report on the spectroscopic identification of nine Lyα emitters at $z = 3.13$ with fluxes between $2 \times 10^{-17}$ and $2 \times 10^{-16}$ ergs cm$^{-2}$ s$^{-1}$ obtained with the FORS spectrograph at Unit 1 of the ESO Very Large Telescope (VLT UT1). The spectra of these high-redshift objects show a narrow, isolated Lyα emission with very faint (frequently undetected) continuum, indicating a large equivalent width. No other features are visible in our spectra. Our Lyα emitters are quite similar to those found by Hu, Cowie, and colleagues in 1998. For a flat universe with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ ($\Omega_0 = 0$), the Lyα luminosity of the brightest source is $1.7 \times 10^9$ $L_\odot$, and the comoving space density of the Lyα emitters in the searched volume is $5 \times 10^{-3}$ Mpc$^{-3}$. Using simple population synthesis models, on the assumption that these sources are regions of star formation, we conclude that the nebulae are nearly optically thick and must have a very low dust content in order to explain the high observed Lyα equivalent widths. For the cosmological and star formation parameters we adopted, the total stellar mass produced would seem to correspond to the formation of rather small galaxies, some of which are perhaps destined to merge. However, one of our sources might become a serious candidate for a protogiant spheroidal galaxy if we assumed continuous star formation, a low mass cutoff of 0.1 $M_\odot$ in the initial mass function (IMF), and a flat accelerating universe with $\Omega_0 = 0.2$ and $\Omega_\Lambda = 0.8$. The implied star formation density in our sampled comoving volume is probably somewhat smaller than, but of the same order of magnitude as, the star formation density at $z \approx 3$ derived by other authors from Lyman break galaxy surveys. This result agrees with the expectation that the Lyα emitters are a low-metallicity (or low-dust) tail in a distribution of star-forming regions at high redshifts. Finally, the Lyα emitters may contribute as many H-ionizing photons as QSOs at $z \approx 3$. They are therefore potentially significant for the ionization budget of the early universe.

Subject headings: cosmology: observations — early universe — galaxies: clusters: individual (Virgo) — galaxies: evolution — galaxies: formation — intergalactic medium

1. INTRODUCTION

Lyα-emitting galaxies at high redshift are of much interest for studies of galaxy formation. While early surveys failed to find such objects (e.g., Thompson, Djorgovski, & Trauger 1995), recent narrowband imaging searches with spectroscopic follow-up identified a number of Lyα emitters at high $z$, first in fields near high-redshift QSOs (Hu & McMahon 1996) and later in blank fields (Cowie & Hu 1998; Hu, Cowie, & McMahon 1998; Pascale, Windhorst, & Keel 1998). These Lyα emitters typically have very faint continua and high Lyα equivalent widths, i.e., they may represent an early phase of galaxy formation when substantial amounts of dust had not yet formed.

Here we report on the discovery of nine Lyα emitters at redshift $z = 3.1$ during our program of studying the intracluster planetary nebula (PN) population in the Virgo cluster, which uses similar narrowband imaging techniques to identify candidate PNs. The first indication of the exis-
tence of a diffuse intracluster stellar population in Virgo was the discovery by Arnaboldi et al. (1996) that a few PNs in the galaxy NGC 4406 (M86; redshift ~230 km s$^{-1}$) have redshifts typical of the Virgo cluster (around +1300 km s$^{-1}$). Subsequently, direct evidence for red giant stars belonging to this stellar population was reported by Ferguson, Tanvir, & von Hippel (1998). Because PNs offer the chance to measure radial velocities and perhaps even abundances for such a diffuse population, a search for intracluster PNs in different positions across the Virgo cluster started immediately and produced several dozens of PN candidates (Méndez et al. 1997; Feldmeier, Ciardullo, & Jacoby 1998) in a total surveyed area of 0.23 deg$^2$.

The “on-band/off-band” narrowband filter technique used to discover the PN candidates (see, e.g., Jacoby et al. 1992) allows the detection of a single emission line. This is not necessarily the desired $\text{[O II]} \lambda 5007$; it might be another emission line at higher $z$, redshifted to the on-band filter—for example, $\text{[O II]} \lambda 3727$ at $z = 0.35$ or $\text{Ly} \alpha$ at $z = 3.13$. In previous work (Méndez et al. 1997), we argued that most of our detections had to be real PNs because (1) the surface density of emission-line galaxies derived from earlier studies was not high enough to explain all the detections; (2) the luminosity function of the detected sources is in good agreement with the PN luminosity functions derived in several Virgo galaxies (Jacoby, Ciardullo, & Ford 1990).

We have used the first ESO Very Large Telescope (VLT) unit (UT1) with the Focal Reducer and Spectrograph (FORS) in multiobject spectroscopic mode and the 4 m Anglo-Australian Telescope (AAT) with the 2 degree field (2df) fiber spectrograph. Our purpose was to confirm the nature of the Virgo intracluster PN candidates, to measure their radial velocities, and (in the VLT case) to detect the faint diagnostic lines required for abundance determinations.

This paper reports on the results of the VLT+FORS observations. The AAT+2df observations, which confirm the existence of Virgo intracluster PNs through the detection of both the $\lambda 4959$ and $\lambda 5007$ $\text{[O III]}$ lines (Freeman et al. 2000), will be presented and discussed by K. C. Freeman et al. (2000, in preparation).

2. OBSERVATIONS AND FIRST RESULTS

For the purpose of detecting faint nebular diagnostic lines with VLT+FORS (ESO program 63.N-0530), we selected Field 1 of Feldmeier et al. (1998) as our first priority, because it had the brightest PN candidates, with a luminosity function cutoff about half a magnitude brighter ($m_{5007} = 25.8$) than elsewhere in the Virgo cluster (see Feldmeier et al. 1998). The total area of Field 1 is 256 arcmin$^2$. We also wanted to use FORS (ESO program 63.I-0007) to verify the PN nature of candidates in the smaller “La Palma Field” (50 arcmin$^2$; Méndez et al. 1997), with magnitudes $m_{5007}$ between 26.8 and 28.6. The lack of bright PNs in the La Palma Field was understandable in Méndez et al. (1997) as a consequence of the sample size effect: if the total PN sample is small, the chance of finding a bright PN is too small.

The observations were made with FORS at the VLT UT1 on the nights of 1999 April 11/12, 15/16, 16/17, and 19/20. Since the FORS field is slightly smaller than $7' \times 7'$ (with the standard collimator), we selected a portion of Field 1 where several of the brightest candidates were located and took on-band and off-band images of the selected portion of Field 1 and of the La Palma Field on the night of April 11/12 using FORS in imaging mode.

The on-band and off-band interference filters we used have, respectively, central wavelengths of 5039 and 5300 Å, and FWHMs of 52 and 250 Å. Some 50 stellar images in the short on-band and off-band FORS exposures (10 and 3 minutes, respectively) were used together with the corresponding stellar images in the Kitt Peak and La Palma discovery images to define coordinate transformations that gave the pixel values of the positions of the PN candidates in the FORS images, given the pixel values of their positions in the discovery images. This way it was possible to define the FORS slit position with sufficient accuracy (in fact, the brightest PN candidates were visible in the short on-band FORS exposures, allowing us to verify directly the accuracy of the pixel transformation, with typical errors below 0.5 pixels, which is equivalent to 0.1').

On the night of April 15/16, R. P. K. and R. H. M. started FORS multiobject spectroscopy (MOS) in Field 1, using grism 300 V without any order separation filter, for maximum spectral coverage. This grism gives a spectral resolution of about 10 Å, at 5000 Å, for slitlets 1" wide. Of the 19 available slitlets, 10 were placed at the positions of PN candidates (numbers 1, 4, 5, 6, 16, 17, 21, 26, 27, 42, ordered by brightness as measured by Feldmeier). These candidates had magnitudes $m_{5007}$ between 25.8 and 26.4. The remaining nine slitlets were placed on stars or galaxies in the field to check the slitlet positioning (which was done by taking a short exposure without grism through the slitlets) and to help locate the dispersion lines as a function of position across the field (which is important in the case of spectra consisting of isolated emission lines).

After taking five exposures of 40 minutes each in Field 1, all with the same slitlet configuration, and having made preliminary on-line reductions, it was clear that the $\text{[O III]}$ emission line candidates were not PNs. Object 1 showed one strong isolated emission line at 5021 Å. It cannot be $\text{[O III]} \lambda 5007$ because there is no hint of the companion line $\lambda 4959$ at the corresponding wavelength. Object 5 was identified as a starburst with $z = 0.35$; it shows narrow emission lines with a continuum, $\lambda 3727$ is redshifted into the on-band filter, and $\text{H} \delta$ and the $\text{[O III]}$ lines $\lambda 4959$ and 5007 are visible, also redshifted with $z = 0.35$. Object 17 was not detected. The remaining seven objects were identified as continuum objects. Many of them are galaxies: they show redshifted emissions.

In summary, none of the candidates tested in Field 1 with VLT+FORS are PNs. This result in fact solves a problem, because these Field 1 candidates were surprisingly abundant and were somewhat brighter than typical PNs in the Virgo galaxies (see the discussion by Feldmeier et al. 1998). The high percentage of continuum objects (seven of nine detections) indicates that the off-band exposure by Feldmeier et al. was not deep enough. A reexamination of the Field 1 images by J. Feldmeier has subsequently confirmed that because of sudden changes in the seeing and transparency the off-band does go to a brighter limiting magnitude than intended. Briefly, the Field 1 exposures consisted of three 3600 s on-band exposures and five 600 s off-band exposures taken at the Mayall 4 m telescope. The additional off-band exposures were intended to compensate for the transparency, which was decreasing at the time of the exposures. Unfortunately, although these additional exposures
do compensate partially for the change in transparency, the seeing increased by 0\'3 and, consequently, the mean off-band exposure is not deep enough.

On the other hand, Freeman et al. (2000) did confirm spectroscopically some fainter PN candidates in Field 1. Taken together, these results imply that the surface density of the intracluster stellar population originally estimated for Field 1 has to be reduced (K. C. Freeman et al., 2000, in preparation).

In view of the result in Field 1, we immediately pointed the VLT UT1 to the La Palma field. In this field, 12 PN candidates were found, 11 reported in Méndez et al. (1997) and one found afterward. The distribution of the 12 PN candidates in the sky made it impossible to assign slitlets to all of them in one slitlet configuration. In our first configuration, we defined 1" wide slitlets for nine PN candidates and two objects suspected to be QSOs or starbursts because they were visible (although much weaker) in the off-band discovery image (Méndez et al. 1997). On the nights of April 15/16 and 16/17, we completed five MOS exposures (40 minutes each) of the initial slitlet configuration, and on April 19/20 we took three additional MOS exposures of the La Palma Field (again 40 minutes each) with a different slitlet configuration, which allowed us to add one PN candidate not observed before.

Thus spectra for a total of 10 PN candidates were acquired in the La Palma Field, and seven were detected. They all show an isolated and narrow emission at wavelengths from 5007 to 5042 Å. A faint continuum is visible only longward of 3760 Å, which is consistent with the position of the Lyman break. Other features visible are O iv λ1035 at 4275 Å, O iv + Si iv λ1402 at 5790 Å, and He ii λ1640 at 6775 Å.

3. ANALYSIS OF THE LA PALMA FIELD SPECTRA

The CCD reductions were made using IRAF\textsuperscript{4} standard tasks. After bias subtraction, flat-field correction, and image combination to eliminate cosmic ray events, the object spectra were extracted and the sky background subtracted. Then the He-Ar-Hg comparison spectra were extracted and the object spectra were wavelength calibrated. Spectrograms of the standard stars G138-31 and G24-9 (Oke 1990) were used for the flux calibration.

We have designated the La Palma Field sources with LPF plus a number ordered according to the brightness in the discovery image. LPFnew is the latest PN candidate, found after the discovery paper (Méndez et al. 1997) was published. Object LPFs1 is the QSO, and LPFs2 is the

\textsuperscript{4} IRAF is distributed by the National Optical Astronomical Observatories, operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation of the United States.
object identified as a starburst from the start because of its stronger continuum. F1-1 and F1-5 are objects 1 and 5 in Feldmeier's Field 1. F1-1 turns out to also have a very faint continuum. F1-1 and F1-5 are objects 1 and 5 in the La Palma Field PN candidates showing no detectable continuum, which is barely visible in the final processed spectrogram.

Figures 1, 2, and 3 show, respectively, the spectra of the QSO, the starburst with visible continuum, and one of the La Palma Field PN candidates showing no detectable continuum. All the LPF PN candidates look very similar, with only one emission line detected across the whole spectrum.

Having found no direct evidence of [O III] λ4959, we would be expected if the detected emission line were λ5007, we can put an upper limit to the percentage of our emission-line objects that can be PNs. After rejecting objects that show a continuum, which clearly cannot be PNs, we proceed in the following way:

1. shift the spectra, so that the wavelengths of the detected emission lines fall at 5007 Å;
2. normalize the intensities of the emission lines to the same value, e.g., 300;
3. add all the spectra and measure the intensity of the resulting λ4959. If it is 50, for example, comparing with the expected value of 100 (since λ5007 was defined to be 300), we can argue that 50% of the objects must be PNs.

The result of this test is shown in Figure 4, where we have added the normalized spectra of the seven PN candidates detected in the La Palma Field. The complete absence of λ4959 indicates that, at most, one of the seven candidates can be a PN. This conclusion is based on the noise level, not on any marginal detection of λ4959. Besides, there is in Figure 4 a hint of a weak continuum, not detectable in the individual spectra, which reinforces the rejection of these candidates as PNs.

4. IDENTIFICATION OF THE DETECTED EMISSION LINE AS Lyα

Having rejected [O III] λ5007, because λ4959 is not visible in Figure 4, we consider the alternatives.

1. [O II] λ3727 at z = 0.35 was confirmed in one case (object 5 in Field 1) but can be rejected in all other cases because we do not see Hβ, [O III] λλ4959, 5007, and Hα at the corresponding redshifted wavelengths. This is illustrated in Figures 5 and 6.
2. Mg II λ2798 at z = 0.79 can also be rejected for a similar reason: in this case we do not see [O II] λ3727 at the expected redshifted wavelength, as illustrated in Figure 7. The same argument can be applied to other lines: assuming C III λ1909, we do not see λ2798; and so on.

We conclude that the isolated emission line must be Lyα at z = 3.1. This identification is supported by the strength of the line: since we see at most a very faint continuum, the equivalent width is fairly large, typically 200 Å (observed) and 50 Å (rest frame). We have mentioned in Méndez et al. (1997) that very few starburst galaxies show, for example, [O II] λ3727 stronger than 100 Å in equivalent width.

5. IMPLICATIONS FOR THE SURFACE DENSITY OF INTRACLUSTER PNs IN VIRGO

A reliable estimate of the surface density of intracluster PNs in Virgo will have to await a survey of a sufficiently large area on the sky, which is currently in progress. Our results to date and some preliminary conclusions are as follows.

No PN candidates have been confirmed in the La Palma Field. Only five of the 12 candidates have a chance of remaining as PNs: two were not tested and three were tested but not detected. Since we have identified most of these candidates as Lyα emitters, it is clear that the intracluster PN sample size in the La Palma Field and the inferred surface density must be substantially smaller than we estimated.

On the other hand, the AAT+2df multiobject fiber spectroscopy has confirmed the existence of intracluster PNs in Fields 1 and 3 of Feldmeier et al. (1998). This will be reported in detail by K. C. Freeman et al. (2000, in preparation). These PNs are brighter than m5007 = 27. Freeman et al. will show that the contamination by Lyα emitters at these brighter magnitudes is not as important as in the La Palma Field. Thus it appears that the fraction of Lyα emitters in [O III] narrowband-selected samples is magnitude-dependent and that it increases toward fainter values of m5007.
EMITTERS AT REDSHIFT \( z \approx 3.1 \)

Fig. 5.—Upper spectrum corresponds to an anonymous galaxy in the La Palma Field that happened to show strong emission at \([\text{O ii}]\) \( \lambda 3727 \), H\( \beta \) and \([\text{O iii}]\) \( \lambda \lambda 4959, 5007 \). We use this object as reference; its continuum has been arbitrarily rectified for easier comparison. Below this star-forming galaxy, we show the spectrum of F1-5 (object 5 in Field 1), redshift-corrected so that the strong emission line detected with the on-band filter falls at 3727 \AA. F1-5 shows the same set of starburst emission lines as the reference galaxy; therefore, its redshift is confirmed to be 0.35. Below we have plotted the spectra of our sources, all redshift-corrected in the same way as F1-5. The levels of zero intensity are separated by 500 counts. None of these sources shows other emission lines at the relevant wavelengths.

The lack of bright PNs in the La Palma Field implies a lower surface density than in other Virgo cluster positions and may indicate some degree of clustering in the distribution of the diffuse intracluster population.

Our VLT + FORS observations have shown that a spectroscopic confirmation of intracluster PN candidates, involving the detection of both the \( \lambda \lambda 4959 \) and 5007 \([\text{O iii}]\) emission lines, is necessary.

6. OBSERVED PROPERTIES OF THE HIGH-REDSHIFT Ly\( \alpha \) EMITTERS

Table 1 collects some basic information about the narrow-lined sources: the measured Ly\( \alpha \) fluxes, measured Ly\( \alpha \) wavelengths, redshifts, and Ly\( \alpha \) equivalent widths (\( W_\lambda \) in almost all cases lower limits because the continuum is not detected). The measured wavelengths provide yet another argument favoring the interpretation of all these sources as unrelated to the Virgo cluster: they are randomly distributed across the on-band filter transmission curve, with no concentration at the Virgo cluster redshift (between 5020 and 5030 \AA; see Fig. 8).

Notice that object LPF3 is brighter than measured in the discovery image. The reason is that in this case Ly\( \alpha \) falls near the edge of the on-band filter transmission curve. LPF3 is remarkable also for the very large lower limit to its Ly\( \alpha \) equivalent width.

The observed fluxes are between \( 2 \times 10^{-17} \) and \( 2 \times 10^{-16} \) ergs cm\(^{-2}\) s\(^{-1}\). We are looking into a small redshift range, defined by the transmission of the on-band filter used at La Palma, of about \( \Delta z \approx 0.04 \). The La Palma Field covers 50 arcmin\(^2\). The total Ly\( \alpha \) flux measured within our “discovery box” is \( 5 \times 10^{-16} \) ergs cm\(^{-2}\) s\(^{-1}\). Adopting \( z = 3.13 \), \( H_0 = 70 \) km s\(^{-1}\) Mpc\(^{-1}\) and \( q_0 = 0.5 \), we get a luminosity distance of \( 1.8 \times 10^4 \) Mpc, which implies Ly\( \alpha \) luminosities for our sources between \( 2 \times 10^8 \) and \( 2 \times 10^9 \) \( L_\odot \). The total Ly\( \alpha \) luminosity within the sampled volume is \( 5 \times 10^9 \) \( L_\odot \). The sampled comoving volume is 1650 Mpc\(^3\), which gives from eight sources a comoving space density \( 5 \times 10^{-3} \) Mpc\(^{-3}\).

These numbers depend on our assumptions about the cosmological parameters: for a flat universe with \( \Omega = 0.2 \), \( \Omega = 0.8 \), and the same \( z \) and \( H_0 \) as above, the luminosity distance becomes \( 3 \times 10^4 \) Mpc, the sampled comoving volume \( 10^4 \) Mpc\(^3\), and the Ly\( \alpha \) luminosities become larger by a factor of 2.8.

7. STARBURST MODELS AND DERIVED QUANTITIES

What produces the narrow Ly\( \alpha \) emission? Given restframe equivalent widths below 200 \AA, the most probable source of ionization is massive star formation (Charlot & Fall 1993). Active galactic nuclei (AGNs) might be an alternative, although there is no hint of C IV 1550 in our spectra,
as is shown in Figure 9. We have taken massive star formation as our working hypothesis.

We have made a simple population synthesis model to explore some basic properties of the stellar population responsible for the ionization of the H II regions. Our main interest in doing this analysis is to estimate star formation rates (SFRs) and densities; we would like to verify whether these Lyα sources correspond to the formation of massive galaxies or to the formation of smaller structures.

We adopt a standard initial mass function (IMF), $f(M) \propto M^{-2.35}$, stellar evolutionary models for low metallicity ($Z = 0.001$; this choice of metallicity will be justified in the next paragraph) from Schaller et al. (1992), and ionizing fluxes from non-LTE atmospheres with winds (Pauldrach et al. 1998), again for a low metallicity, in this case, that of the SMC (five times below solar).

The relation between the number of stellar Lyman continuum photons $N_{LyC}$ and the Lyα luminosity can be obtained from a simple recombination model:

$$L(Lyα) = hν(Lyα)0.68X_B N_{LyC},$$

where 0.68 is the fraction of recombinations that yield Lyα (Case B; see, e.g., Storey & Hummer 1995), and $X_B$ is the product of the fraction of $N_{LyC}$ really absorbed times the fraction of Lyα photons that really escape. We necessarily have $0 \leq X_B \leq 1$. Note that $X_B \sim 1$ requires both an optically thick nebula and very low dust content, because the large number of Lyα scatterings in an optically thick nebula will lead to their absorption by dust grains, if such grains are present in any significant number. This explains our

| Object   | Fluxa | $λ$ (Å) | $z$ | $W$ (Å)b | $M_{\text{star}}c$ | SFRd | $M_\odot$ & SFRd |
|----------|-------|---------|-----|----------|-------------------|------|-----------------|
| LPFs2    | 17    | 5011    | 3.121 | 33       | 21-420            | 7-140| 5-10            |
| LPF1     | 7     | 5011    | 3.121 | $\geq 55$ | 9-75              | 3-25 | 2-3             |
| LPF2     | 6     | 5026    | 3.133 | $\geq 32$ | 7-150             | 3-50 | 2-4             |
| LPF3     | 10    | 5042    | 3.146 | $\geq 175$ | 8-11              | 3-4  | ...             |
| LPF4     | 3     | 5007    | 3.118 | $\geq 14$ | 4-270             | 1-90 | 1-5             |
| LPF6     | 2     | 5035    | 3.140 | $\geq 70$ | 3-14              | 1-5  | 0.4-0.5         |
| LPF8     | 2     | 5034    | 3.140 | $\geq 37$ | 3-44              | 1-15 | 0.6-1           |
| LPFnew   | 2     | 5010    | 3.120 | $\geq 25$ | 3-65              | 1-22 | 0.6-2           |
| F1-1     | 15    | 5021    | 3.129 | 45       | 19-200            | 6-67 | 4-6             |

a Measured Lyα fluxes in units of $10^{-17}$ ergs cm$^{-2}$ s$^{-1}$. Using the luminosity distance of $1.8 \times 10^8$ Mpc, this column also gives the Lyα luminosities, in units of $10^8 L_\odot$.

b Equivalent widths of Lyα transformed into the rest frame (the measured widths are $z + 1$ times larger).

c Possible range of total stellar mass formed, in units of $10^8 M_\odot$, assuming starbursts of $3 \times 10^9$ yr duration; see §7 and Fig. 14.

d Possible range of star formation rates, in $M_\odot$ yr$^{-1}$, assuming starbursts; see §7.

e Possible range of total stellar mass formed, in units of $10^7 M_\odot$, assuming continuous star formation over $10^9$ yr; see §7 and Fig. 15. The same numbers also represent the corresponding star formation rates in $M_\odot$ yr$^{-1}$.
choice of a low metallicity. How low is low? Since we do not know much about dust properties, we have used empirical information provided by Charlot & Fall (1993) in their Figure 8, which shows Lyα equivalent widths as a function of oxygen abundance in nearby star-forming galaxies. In that figure, we find that Lyα equivalent widths larger than 20 and 50 Å are associated, respectively, with oxygen abundances below 25% and 10% solar. In future work, to obtain more quantitative constraints, we intend to carry out Lyα radiative transfer calculations in the presence of dust and velocity fields as an extension of the work by Hummer & Kunasz (1980), Hummer & Storey (1992), and Neufeld (1990, 1991).

Figures 10 and 11 show Lyα equivalent widths for single stars as a function of $X_B$ and of the stellar $T_{\text{eff}}$. We need both a large $X_B$ and many massive, hot main-sequence stars to produce the observed Lyα equivalent widths.

We have explored two different histories of star formation in a low-metallicity stellar population: (1) a starburst, and (2) continuous star formation. These two alternatives are defined as star formation extending over a time (1) similar to $(3 \times 10^6 \text{ yr})$ and (2) much longer than $(10^9 \text{ yr})$ the duration of a main-sequence OB star.

Figures 12 and 13 show the resulting contour plots of Lyα equivalent widths as a function of $X_B$ and of the maximum main-sequence mass in the population. In these figures, the quantities on the x-axis allow different interpretations. In the case of a starburst, smaller values of $M_{\text{max}}$ can be interpreted to represent an increasing age of the starburst or, in other words, the time elapsed since the starburst happened; as the starburst grows older, the most massive stars are removed from the main sequence. In the case of continuous

Fig. 8.—The solid line is the transmission curve of the on-band filter used at La Palma. The histogram shows the wavelength distribution of the emission lines. One object corresponds to 1 unit along the y-axis. Our sources are more or less uniformly distributed across the filter curve.

Fig. 9.—Spectra of our sources in the rest frame of Lyα. At the top is the QSO LPFs1. The levels of zero intensity are separated by 500 counts. Only the QSO shows C IV λ1550. At some wavelengths, a slightly larger noise level is noticeable; this is caused by imperfect sky subtraction in the presence of very strong sky emission lines. In several cases where the disturbance by the sky lines was too bad, we have replaced the spectrum by a straight line at zero intensity.
star formation, the value of $M_{\text{max}}$ indicates at which mass the integration of the IMF was stopped. In other words, the left part of the plot shows a case in which very massive main-sequence stars were not formed.

We can obtain Ly$\alpha$ equivalent widths greater than 50 Å only for $X_B > 0.5$ (continuous star formation) or $X_B > 0.3$ (starburst). This points to almost completely optically thick, extremely dust-poor nebulae. It is easy to understand why a large $X_B$ is necessary. If it is small, many stellar ionizing photons are lost. To explain the observed Ly$\alpha$ fluxes we must add more massive stars, but these stars make a strong contribution to the continuum; therefore, the Ly$\alpha$ equivalent width must decrease.

It may seem surprising that we can get large Ly$\alpha$ equivalent widths at such low values of $X_B$. The reason is that the Schaller et al. main sequence at low metallicity is shifted to rather high $T_{\text{eff}}$ because of the low stellar opacity. This means that lower mass objects on the main sequence give much more ionizing flux than at solar metallicity.

The source LPF3 can be explained only as a very young starburst with $X_B \sim 1$ because of its very large Ly$\alpha$ equivalent width.

We set the lower mass limit of the Salpeter IMF at 0.5 $M_\odot$. For a maximum stellar mass of 120 $M_\odot$, this gives an average mass of 1.65 $M_\odot$, which is then the conversion factor between the number of stars and the total stellar mass. The average mass decreases only slightly if we decrease $M_{\text{max}}$, and only if $M_{\text{max}}$ is interpreted as in Figure 13, because in that case very massive stars are not formed. The average mass does not decrease if $M_{\text{max}}$ is low owing to the age of the starburst because the very massive stars are assumed to have formed and evolved away from the main sequence.

Figures 14 and 15 show contour plots of the logarithms of Ly$\alpha$ luminosities in a plane where the $x$-axis is the same $M_{\text{max}}$ used in Figures 12 and 13, and the $y$-axis is the product of $X_B$ times the total number of stars produced over the total duration of the star formation ($3 \times 10^6$ and $10^9$ yr, respectively). The number of stars required to produce a given Ly$\alpha$ luminosity depends on the value of $M_{\text{max}}$. Since we cannot determine $M_{\text{max}}$ empirically or derive it from first principles, we have considered the full range of $M_{\text{max}}$, from 120 $M_\odot$ to as low as permitted by the limits on the Ly$\alpha$ equivalent widths; sometimes as low as 20
The average stellar mass of 1.65 $M_\odot$ we have built Table 2, Table 3, formed, and the resulting SFR, needed to explain our total which provides the total number and total mass of stars

$M_\odot$. This produces rather large uncertainties in the derived masses, particularly in the case of starbursts. A comparison of Figures 14 and 15 also shows that, as expected, in the case of continuous star formation many more stars are needed to obtain a given Lyman luminosity.

The results of these mass estimates are listed in Table 1. The total masses of stars and star formation rates turn out to be very sensitive to the star formation history. For continuous star formation and young starbursts, i.e., high values of $M_{\text{max}}$, our strongest sources have SFRs of the order of 10 $M_\odot$ yr$^{-1}$. However, these numbers increase dramatically if we consider older starbursts, and we cannot rule out SFRs higher than 200 yr$^{-1}$ in a few cases.

Adding up the masses and SFRs in Table 1, and using the average stellar mass of 1.65 $M_\odot$, we have built Table 2, which provides the total number and total mass of stars formed, and the resulting SFR, needed to explain the total Lyman luminosity of 5 $\times$ 10$^9$ L$\odot$ in the La Palma Field for the cases of starbursts and continuous star formation. Here we have not added the numbers for F1-1, which belongs to another field.

How uncertain are these numbers? First of all, the real SFR might be higher than we inferred for our sources because of extinction by dust. However, we consider this to be unlikely because it would be necessary to argue that there is dust in the foreground (to produce extinction) but not inside (it would destroy the Lyman emission). We do not argue in terms of low metallicity because there is at least one case of a very metal-deficient blue compact dwarf galaxy, SBS 0335−052, where dust patches are clearly visible (Thuan & Izotov 1999). Note however that this source has Ly$\alpha$ in absorption, implying that extinction is accompanied by destruction of Ly$\alpha$ emission, as expected. Based on this reasoning, we do not include a correction for extinction in our tables.

The reader may argue that geometry probably plays the dominant role in dictating how many Ly$\alpha$ photons escape, making our attempt to estimate star formation rates a futile exercise. However, our sources are a rather special case. Geometry is useful when we need to explain why a star-forming region shows Ly$\alpha$ in absorption; see, e.g., Kunth et al. (1998). But our sources do show strong Ly$\alpha$ emission and, furthermore, show a very faint continuum. The absence of continuum (i.e., the large equivalent width of Ly$\alpha$) is very important because it precludes the existence of large amounts of hot stars. If there is any significant destruction of Ly$\alpha$ photons, then, to explain the observed Ly$\alpha$ fluxes we must add more massive stars. But these additional stars contribute to the continuum, and the Ly$\alpha$ equivalent width decreases too much. Thus the absence of continuum acts as a “safety valve” restricting higher values of the star formation rate. As explained above, extinction by dust is not very likely.

On the other hand, the derived masses and SFRs are strongly dependent on the lower mass limit of the IMF. If we selected a lower mass limit of 0.1 instead of 0.5 $M_\odot$, there would be no change in the number of stars needed to produce the ionizing photons, but we would be adding a lot of low-mass stars; the total mass estimate for a given total Ly$\alpha$ luminosity would increase by a factor of 1.9. The SFRs would have to be corrected by the same factor. The ranges of masses and SFRs in Tables 1 and 2 do not include this source of uncertainty, but we will take it into account in the discussion.

The adopted cosmological parameters also have some influence. We have adopted $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$, which implies a sampled comoving volume of 1650 Mpc$^3$. If we take, for example, a total SFR of 50 $M_\odot$ yr$^{-1}$, we get a star formation density in the comoving volume of 0.03 $M_\odot$ yr$^{-1}$ Mpc$^{-3}$. If we adopted a universe with $\Omega_0 = 0.2$, $\Omega_0 = 0.8$, but with the same $z$ and $H_0$, then our star masses and SFRs would be larger by the same factor 2.8 as for the luminosities. However, the star formation density mentioned above would drop from 0.03 to 0.014 $M_\odot$ yr$^{-1}$ Mpc$^{-3}$ because of the enlarged sampled comoving volume of 10$^4$ Mpc$^3$.
8. DISCUSSION

Recent blank field searches for Lyα emitters have been successful at redshifts from 2.4 to 5 (Hu 1998; Cowie & Hu 1998; Pascarelle et al. 1998; Hu et al. 1998). The sources that have been verified spectroscopically (Hu 1998; Hu et al. 1998) are like ours: strong, narrow, isolated emission line identified as Lyα, with a similar range of equivalent widths.

One may ask why the earlier searches failed to detect such emission-line sources. For example, Thompson et al. (1995) reported no detection in a total area of 180 arcmin² down to a 1σ limiting flux 10 times fainter than the flux of our brightest source, LPFs2. This might be attributed to a very low surface or space density in their directions, but since they looked in many directions, this interpretation is improbable. The surface density in the La Palma Field does not seem to be abnormally high. The eight sources we detected in the 50 arcmin² of the La Palma Field and within our redshift range of 0.04 are equivalent to 14,400 emitters deg⁻² per unit z with Lyα fluxes above $1.5 \times 10^{-17}$ ergs cm⁻² s⁻¹. This is a lower limit to the true density of such sources; if some of the three photometric candidates not detected and of the two candidates not tested are Lyα emitters with similar fluxes, the true density could be higher by up to 60%. The density inferred from the present spectroscopic sample is similar to the 15,000 deg⁻² per unit z reported by Hu et al. (1998) from Keck searches in different regions of the sky, with the same limiting flux. Our sources are brighter than those detected with the Keck telescope (Hu 1998; Cowie & Hu 1998; Hu et al. 1998), but our redshift is smaller (see Fig. 16). In summary, the surface density of Lyα emitters in the La Palma Field is of the same order of magnitude as for the sources detected by Hu et al. Pascarelle et al. (1998) report an order-of-magnitude range of space densities at $z = 2.4$, in some cases even higher than ours. More surveys probably will clarify whether or not there is any structure or clustering in the distribution of Lyα emitters.

Concerning masses and star formation rates, if we adopt continuous star formation or young starbursts, where star formation has not yet (or has just) stopped, then from Table 1 we read that our strongest sources show an SFR not higher than about $10 M_{\odot}$ yr⁻¹, similar to the maximum SFRs reported by Hu et al. (1998) and short of what would be expected from a protogiant spheroidal galaxy forming more than $10^{11} M_{\odot}$ in 10⁷ yr. We cannot completely rule out the possible existence of an inconspicuous stellar population, already formed, which would be detectable only in the infrared, but we would find it difficult to explain the very low dust content in that case. The possible existence of undetected neutral and molecular H gas would provide additional means to scatter and eventually destroy the Lyα photons (e.g., Neufeld 1990); therefore, we consider it unlikely. Thus, from the available evidence, we would seem to be witnessing the formation of small subgalaxies, some of which are perhaps destined to merge. This conclusion is also supported by the total mass produced, even in the case of continuous star formation, and would be unchanged if we adopted the lowest IMF mass limit of 0.1 $M_{\odot}$. If we also adopted the flat accelerating universe with $\Omega_0 = 0.2$ and $\Omega_{\Lambda} = 0.8$, which implies larger distances, luminosities, and SFRs, the starbursts would still point to small entities, but the continuous star formation in the case of LPFs2 would be able to produce several times $10^{10} M_{\odot}$.

On the other hand, continuous star formation implies the previous production of supernovae and metals, which makes it more difficult to explain a very low dust content. For that reason, we consider young starbursts more likely than continuous star formation or old starbursts, but in dealing with this subject we prefer to be cautious and leave all conceivable options open.

What would happen if we allowed for older starbursts, in which star formation has stopped 10⁷ yr ago? Then the mass of stars formed would increase substantially, but notice that in such cases the mass produced after star formation has stopped is not larger than $10^9 M_{\odot}$. Therefore, even in this extreme case, starbursts are not able to make a protogiant spheroidal galaxy out of any of our sources. This conclusion would not be weakened by assuming the accelerating universe mentioned above.

Now we try to estimate lower and upper limits for the star formation density in the sampled comoving volume that corresponds to the La Palma Field, assuming that we can rule out production of Lyα photons through AGN activity. A lower limit for the SFR of $15 M_{\odot}$ yr⁻¹ comes from the continuous star formation case in Table 2. The maximum SFR in Table 2 (old starbursts) is rather improbable because it is obtained assuming that all the starbursts ended at the same time, some 10⁷ yr before the Lyα photons we detected were emitted. A more reasonable upper limit is obtained assuming that one of the starbursts is at the right age to produce the maximum SFR, while all the others make smaller contributions. Let us assume that the source produced by the only allowed old starburst is LPFs2, which would then contribute $140 M_{\odot}$ yr⁻¹. Adding the almost negligible contributions from the other sources, we obtain in this way a range of plausible total SFRs in the comoving volume between 15 and 170 $M_{\odot}$ yr⁻¹. Allowing now for the uncertainty in the lower mass limit of the IMF, we get a range between 15 and 320 $M_{\odot}$ yr⁻¹, which implies a star formation density between 0.009 and 0.19 $M_{\odot}$ yr⁻¹ Mpc⁻³. For comparison, Hu et al. (1998) obtained, from their own samples, 0.01 in the same units.

To compare our star formation density with other available information, we adopt in this paragraph $H_0 = 50$ km s⁻¹ Mpc⁻¹ and $q_0 = 0.5$, which is what other authors have done, e.g., Steidel et al. (1999). This gives luminosities twice

![Fig. 16.—Logarithms of observed Lyα fluxes (in ergs cm⁻² s⁻¹) as a function of redshift. The plus signs are our sources, and the vertical bars represent the ranges of fluxes observed by Hu (1998) at redshifts 3.4 and 4.6. The dashed lines represent the observed fluxes for Lyα luminosities of $10^{42}$ and $10^{44}$ ergs s⁻¹, if we assume $H_0 = 70$ km s⁻¹ Mpc⁻¹ and $q_0 = 0.5$.](image)
as large as in our earlier choice, and a sampled comoving volume of 4500 Mpc$^3$. Our resultant star formation density drops slightly to between 0.007 and 0.14 M$_\odot$ yr$^{-1}$ Mpc$^{-3}$. This is plotted in Figure 17 together with other data collected from several galaxy surveys by Steidel et al. (1999). Our star formation density in Ly$\alpha$ emitters is comparable to that in other star-forming sources at that redshift. Our sources are probably the low-metallicity (or low-dust) tail in a distribution of star-forming regions at high redshifts. This is underlined by the fact that in our sampled volume we also have a QSO (LPFs1) with apparently higher metal abundances, judging from the strength of the C, N, and O lines in its spectrum.

As already remarked by Hu et al. (1998), since we expect lower metallicity at higher redshifts, we should expect the strong Ly$\alpha$ emitters to become more frequent at higher redshifts relative to Lyman break galaxies, which normally have weak or absent Ly$\alpha$ emission and are therefore presumably more metal-rich. Note, however, that low metallicity does not necessarily imply emission in Ly$\alpha$: the blue compact dwarf galaxy SBS 0335−0052 (Thuan & Izotov 1999), with $Z \approx Z_\odot/41$ and Ly$\alpha$ in absorption, provides a beautiful cautionary note. Kunth et al. (1998) have argued that the geometry and velocity structure of the interstellar medium play an important role in determining the strength of the Ly$\alpha$ emission, and this may complicate the comparison between Ly$\alpha$ emitters and Lyman break galaxies.

Finally, we consider our Ly$\alpha$ emitters as possible sources of ionization of the intergalactic medium at high redshift (see, e.g., Madau, Haardt, & Rees 1999). Keeping the same cosmological parameters as in last paragraph, we get a total \( L(\text{Ly}\alpha) \), in our sampled comoving volume, of $10^{46} L_\odot$. Converting this into \( N_{\text{Ly}\alpha} \) using equation (1), on the assumption that $X_B = 0.5$, we get $7 \times 10^{51}$ photons s$^{-1}$. Since the sampled comoving volume is 4500 Mpc$^3$, this implies an ionizing photon density of $1.5 \times 10^{51}$ photons s$^{-1}$ Mpc$^{-3}$. This is the total number of ionizing photons produced by the stars. It is very difficult to estimate what fraction is available for ionization of the intergalactic medium, because it depends on the relative contributions of the two factors that enter into $X_B$. In at least one case (LPF3), we have $X_B \approx 1$, which means that this source cannot contribute many ionizing photons. Assuming optimistically that there remain $10^{51}$ ionizing photons s$^{-1}$ Mpc$^{-3}$ available, our Ly$\alpha$ emitters seem to contribute about 0.5 times as much as the star-forming galaxies at $z = 3$ found in Lyman break galaxy surveys (see, e.g., Fig. 2 of Madau et al. 1999). We conclude that the contribution by Ly$\alpha$ emitters may be comparable in order of magnitude to what QSOs provide at $z = 3$.

9. SUMMARY OF CONCLUSIONS AND PERSPECTIVES

We have discovered a population of high-redshift Ly$\alpha$ emitters in our sample of Virgo intracluster PN candidates obtained with an “on-band/off-band” filter technique. Our VLT+FORS spectra show that the Ly$\alpha$ emitters at $z = 3.13$ look very similar to those discovered in other fields at other redshifts by Hu et al. (1998). Only a narrow and strong Ly$\alpha$ emission is visible in their spectra; no other spectral line and no (or at most a very weak) continuum is visible. On the assumption that Ly$\alpha$ emission is produced by massive star formation, we have estimated the total mass of stars formed and SFRs, and we have estimated the star formation density in our sampled comoving volume. The Ly$\alpha$-emitting nebulae must be nearly optically thick and extremely dust-poor, probably indicating a very low metallicity. The total mass formed and the SFRs appear to suggest that we are witnessing the formation of rather small galaxies. This conclusion depends on several assumptions about the IMF, star formation history, and cosmological parameters. There is one source (LPFs2) that might qualify as a protogiant spheroidal if we assumed continuous star formation, a lower mass cutoff of 0.1 M$_\odot$ in the IMF, and a flat accelerating universe with $\Omega_0 = 0.2$ and $\Omega_\Lambda = 0.8$. However, to assume continuous star formation implies the previous production of supernovae and metals, making it more difficult to explain the very low dust content required by the observed spectra of our sources. It is more probable that we are dealing with young starbursts.

Taking all sources into account, the implied star formation density in our sampled comoving volume is probably somewhat smaller than, but of the same order of magnitude as, the star formation density at $z \sim 3$ derived by other authors from Lyman break galaxy surveys. This result agrees with the expectation that the Ly$\alpha$ emitters are a low-metallicity (or low-dust) tail in a distribution of star-forming regions at high redshifts. Finally, the Ly$\alpha$ emitters may contribute as many H-ionizing photons as QSOs at $z \sim 3$. They are therefore potentially significant for the ionization budget of the early universe.

More extensive surveys at different redshifts will be needed to build a luminosity function for the Ly$\alpha$ emitters and to decide if they show any evidence of clustering and evolution as a function of redshift. HST images might be able to resolve these sources; their morphology might offer clues about their star formation processes. High-resolution spectroscopy of Ly$\alpha$ would provide important kinematic information about the interstellar medium in these galaxies. We need infrared spectra to try to detect forbidden lines and either determine or put some upper limits to the metallicity.
It might also be possible to clarify to what extent the production of Lyα photons can be attributed to AGN activity. The firm detection of an infrared continuum would help to constrain the characteristics and total mass of the stellar populations through comparison with population synthesis models.

The implications of our results for the surface density of the diffuse intracluster stellar population in the Virgo cluster are not clear yet. Future searches for intracluster PNs will have to include the spectroscopic confirmation of the candidates by detection of the two bright [O III] emissions at 4959 and 5007 Å. From the spectroscopic work of our group to date, including the confirmation of 23 intracluster PNs by the detection of the two [O III] lines by Freeman et al. (2000), the fraction of high-redshift Lyα sources in the on-band/off-band samples appears to be higher at faint magnitudes. In the specific case of the “La Palma Field,” we have not found any intracluster PNs, perhaps suggesting some degree of clumpiness in the distribution of the intracluster stellar population. In other Virgo fields with brighter PN candidates, the fraction of high-redshift Lyα emitters among the detected sources appears to be about 25% (see K. C. Freeman et al., 2000, in preparation, for a more extensive discussion).

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REFERENCES

Arnaboldi, M., et al. 1996, ApJ, 472, 145
Charlot, S., & Fall, S. M. 1993, ApJ, 415, 580
Cowie, L. L., & Hu, E. M. 1998, AJ, 115, 1319
Feldmeier, J. J., Ciardullo, R., & Jacoby, G. H. 1998, ApJ, 503, 109
Ferguson, H. C., Tanvir, N. R., & von Hippel, T. 1998, Nature, 391, 461
Freeman, K. C., et al. 2000, in ASP Conf. Proc. 197, Dynamics of Galaxies: From the Early Universe to the Present, ed. F. Combes, G. A. Mamon, V. Charmandaris (San Francisco: ASP), 389
Hu, E. M. 1998, in ASP Conf Proc. 146, Pushing Back Studies of Galaxies Toward the Dark Ages: High-Redshift Lyα Emission-Line Galaxies in the Field, ed. S. D’Odorico, A. Fontana, & E. Giallongo (San Francisco: ASP), 148
Hu, E. M., Cowie, L. L., & McMahon, R. G. 1998, ApJ, 502, L99
Hu, E. M., & McMahon, R. G. 1996, Nature, 382, 231
Hummer, D. G., & Kunasz, P. B. 1980, ApJ, 236, 609
Hummer, D. G., & Storey, P. J. 1992, MNRAS, 254, 277
Jacoby, G. H., et al. 1992, PASP, 104, 599
Jacoby, G. H., Ciardullo, R., & Ford, H. C. 1990, ApJ, 356, 332
Kunth, D., et al. 1998, A&A, 334, 11
Madau, P., Haardt, F., & Rees, M. J. 1999, ApJ, 514, 648
Méndez, R. H., et al. 1997, ApJ, 491, L23
Neufeld, D. A. 1990, ApJ, 350, 216
———. 1991, ApJ, 370, L85
Oke, J. B. 1990, AJ, 99, 1621
Pascale, S. M., Windhorst, R. A., & Keel, W. C. 1998, AJ, 116, 2659
Pauldrach, A. W. A., et al. 1998, in ASP Conf. Proc. 131, Realistic Models for Expanding Atmospheres, ed. I. Howarth (San Francisco: ASP), 258
Schaller, G., Schaerer, D., Meynet, G., & Maeder, A. 1992, A&AS, 96, 269
Steidel, C. C., et al. 1999, ApJ, 519, 1
Steidel, C. C., et al. 2000, ApJ, 532, 170
Storey, P. J., & Hummer, D. G. 1995, MNRAS, 272, 41
Thompson, D., Djorgovski, S., & Trauger, J. 1995, AJ, 110, 963
Thuan, T. X., & Izotov, Y. I. 1999, preprint (astro-ph/9902369)