Hα TAIL, INTRACLUSTER H II REGIONS, AND STAR FORMATION: ESO 137-001 IN ABELL 3627

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ABSTRACT

We present the discovery of a 40 kpc Hα tail and at least 29 emission-line objects downstream of a star-forming galaxy, ESO 137-001, in the rich, nearby cluster A3627. The galaxy is known to possess a dramatic 70 kpc X-ray tail. The detected Hα tail coincides positionally with the X-ray tail. The Hα emission in the galaxy is sharply truncated on the front and the sides near the nucleus, indicating significant ram pressure stripping. ESO 137-001 is thus the first cluster late-type galaxy known unambiguously to have both an X-ray tail and an Hα tail. The emission-line objects are all distributed downstream of the galaxy, with projected distances of up to 39 kpc from the galaxy. From the analysis on the Hα emission frame and the estimate of the background emission-line objects, we conclude that it is very likely that all 29 emission-line objects are H II regions in A3627. The high surface number density and luminosities of these H II regions (up to $10^{40}$ erg s$^{-1}$) dwarf the previously known examples of isolated H II regions in clusters. We suggest that star formation may proceed in the stripped ISM in both the galactic halo and intracluster space. The total mass of formed stars in the stripped ISM of ESO 137-001 may approach several times $10^7 M_\odot$. Therefore, stripping of the ISM not only contributes to the ICM, but also adds to the intracluster stellar light through subsequent star formation. The data also imply that ESO 137-001 is in an active stage of transformation accompanied by the buildup of a central bulge and depletion of the ISM.

Subject headings: galaxies: clusters: individual (A3627) — galaxies: evolution — galaxies: individual (ESO 137-001) — galaxies: ISM — H II regions — stars: formation

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1. INTRODUCTION

The intracluster medium (ICM) has long been thought to play a vital role in galaxy evolution in clusters (Gunn & Gott 1972). Ram pressure and turbulence/viscous stripping by the ICM can efficiently remove cold galactic gas and may be responsible for transforming disk galaxies with active star formation into red S0 galaxies (e.g., Quilis et al. 2000). Stripping of the galactic interstellar medium (ISM) in clusters has been extensively examined in simulations (e.g., Schulz & Struck 2001, hereafter SS01; Roediger & Hensler 2005, hereafter RH05), which show that stripping has a significant impact on the properties of galaxies. In the process of stripping, the galactic ISM is removed from the disk and the outer galactic disk is truncated, while the inner disk is compressed, accompanied by formation of numerous flocculent arms (SS01; RH05). The galactic star formation rate (SFR) is also modified. Compression of the disk ISM may trigger prodigious star formation (e.g., SS01; Bekki & Couch 2003; RH05) in the first $\sim 10^4$ yr of interaction, even though star formation activity will eventually be suppressed as the galactic ISM is depleted. This initial starburst may explain the blue $\text{Butcher-Oemler}$ galaxies” in $z \geq 0.3$ clusters (Butcher & Oemler 1984). The further evolution of the stripped ISM from the disk is not clear because of uncertainties in the transport coefficients (conductivity and viscosity). It has been suggested that some stripped ISM may be able to cool enough to form stars because the main ISM heating source, stellar UV radiation, is much weaker in intracluster space (e.g., SS01). Therefore, ISM stripping in clusters is important for both galaxy evolution and star formation in clusters.

Observational evidence of stripping in cluster late-type galaxies has only begun to accumulate in recent years. Tails behind late-type galaxies have been observed in H I, Hα, and X-rays (e.g., Gavazzi et al. 2001; Wang et al. 2004; Oosterloo & van Gorkom 2005; Sun & Vikhlinin 2005; Yagi et al. 2007). Recently we found a long X-ray tail in a rich cluster, A3627, associated with a late-type galaxy, ESO 137-001 (Sun et al. 2006, hereafter S06). The narrowness and length of the tail make it the most dramatic X-ray tail of a late-type galaxy discovered to date. It is also the only known X-ray tail from a late-type galaxy in a rich cluster. There are only two other known X-ray tails associated with late-type galaxies in clusters (C153 in A2125: Wang et al. 2004; UGC 6697 in A1367: Sun & Vikhlinin 2005). Both are in $\sim 3$ keV clusters that are more distant than A3627 (note that $z = 0.253$ for A2125). We have also examined all Chandra and XMM-Newton data for $T > 3$ keV clusters at $z < 0.1$ (62 clusters in total; for the work on a subsample at $z < 0.05$, see Sun et al. 2007). No other significant stripped tails of late-type galaxies have been detected, which implies that ESO 137-001’s current stage is of short duration.

A3627 is a nearby rich cluster ($z = 0.01625, \sigma_{\text{radial}} = 925$ km s$^{-1}$, and $kT = 6$ keV) that rivals Coma and Perseus in mass and galaxy content (Kraan-Korteweg et al. 1996; Woudt et al. 2007). ESO 137-001 is a blue emission-line galaxy (Woudt et al. 2004) that is only $\sim 200$ kpc from the cluster’s X-ray peak on the plane of the sky. Its radial velocity (4630 km s$^{-1}$) is close to that of A3627 (4871 $\pm 54$ km s$^{-1}$; Woudt et al. 2007). S06 found a long narrow X-ray tail behind ESO 137-001 in both Chandra and XMM-Newton data (shown in Fig. 1). The tail extends to at least 70 kpc from the galaxy and has a length-to-width ratio of $\sim 10$. The X-ray tail is luminous ($\sim 10^{41}$ ergs s$^{-1}$), with an X-ray gas mass of $\sim 10^7 M_\odot$. S06 interpret the tail as the stripped ISM of ESO 137-001, mixed with hot ICM, while this blue galaxy is being converted into a gas-poor galaxy. The Chandra data also reveal three hard X-ray point sources ($L_X \sim 10^{40}$ ergs s$^{-1}$) along the tail (Fig. 1), and the possibility of all of them being background AGNs is $< 0.1\%$. Thus, we suggested that some of them may be ultraluminous X-ray sources (ULXs) born from active
Fig. 1.—(a) XMM-Newton 0.5–2 keV mosaic of A3627 (background-subtracted and exposure-corrected). A long X-ray tail is significant, as indicated by the white box. The brightest three cluster galaxies (in the $K_s$ band) are away from the cluster gas core (ESO 137-006-1, ESO 137-008-2, and ESO 137-010-3). (b) Zoomed-in image of the region around ESO 137-001’s tail (4.0′ × 4.1′). Chandra contours (from the 0.5–2 keV smoothed image, shown in red) are superposed on the Hα (+continuum) image. The dotted box region is where data in all of the Hα, Hαoff, B, and I bands are available and for which the colors are measured in Fig. 2. Three Chandra point sources in the tail are also marked with red stars. Purple circles mark emission-line objects selected from the colors in Fig. 2, whereas cyan squares mark six more sources selected if the criteria to select emission-line objects are relaxed (‡3.1). The green rectangles mark the regions where surface brightness profiles are measured along the minor and major axes as shown in Fig. 6. The dashed circle (15 kpc in radius) shows the approximate size of the tidally truncated dark matter halo of ESO 137-001 (also shown in panel d). Most of the emission-line objects may still be in the halo, but the most distant three are 29–39 kpc from the nucleus. G1 and G2 are the only two galaxies within 100 kpc from the end of ESO 137-001’s X-ray tail (velocity unknown). The cluster is close to the Galactic plane (Galactic latitude of −7°), so the foreground star density is high. (c) Net Hα emission (smoothed) in a contrast to enhance the emission from the diffuse tail, superposed on the Chandra contours (red). Stars are masked. Beyond the Hα tail and the emission-line objects (in purple circles, for those outside the tail), the residual emission is generally around bright stars. The scale bar is 5 kpc (15.8′). The X-ray leading edge in the current short Chandra exposure is actually around the same position as the Hα edge, as the Chandra contours shown are from a smoothed image. (d) Net Hα emission in the galaxy and the head of the tail (1.1′ × 1.1′). The contours (magenta) around the peaks are also shown. Symbols have the same meaning as in panel b. Eight representative emission-line objects are marked, from ELO1 to ELO8 (including sources 7 and 8 in panel e). The dashed box indicates the aperture used to measure the total net Hα flux from the galaxy (‡4). The scale bar is 10′ (3.17 kpc). (e) Hα (+continuum) image of the same region as in panel d. The nuclear region is also shown with red contours (similar in the next two panels). The scale bar is 10′. (f) I-band image of the same field as panel d. (g) B-band image of the same field as panel d. Two blue features (from the B − I image) downstream of the galaxy are indicated by arrows. There are also broadband features to the south of ELO1.
star formation in the tail. Nevertheless, the optical properties of this interesting galaxy are poorly known in the literature (e.g., Woudt et al. 2004, 2007). In this paper, we present the results from our Hα and optical broadband imaging observations of ESO 137-001 with SOAR and our spectroscopic observations with the CTIO 1.5 m telescope. We adopt a cluster redshift of 0.01625 for A3627 (Woudt et al. 2007), which is a little larger than what we used in S06 (0.0157, from Kraan-Korteweg et al. 1996). If we assume that \( H_0 = 73 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega_M = 0.24 \), and \( \Omega_{\Lambda} = 0.76 \), the luminosity distance is 67.6 Mpc, and \( 1'' = 0.317 \text{ kpc} \).

2. OBSERVATIONS AND DATA REDUCTION

2.1. SOAR Observations

ESO 137-001 was observed with the 4.1 m Southern Observatory for Astrophysical Research (SOAR) telescope on Cerro Pachon on 2006 August 28 (UT) and 2007 March 15 (UT). Both nights were clear and photometric. The observations were made with the SOAR Optical Imager (SOI), which covers a 5.26′′ square field of view with two CCDs (2.6′′ width each, separated by an 8.1′′ gap). In the 2006 run (≈0.7″ seeing, 1.23–1.31 air mass), two 20 minute exposures were collected with the Hα filter and five 20 s exposures were taken in the I band. However, the telescope guider happened to be south of the galaxy in two of the Hα exposures, blocking any emission 26′′ south of the galactic nucleus. In the 2007 run (≈0.9″ seeing, 1.17–1.29 air mass), we took four 20 minute exposures in the Hα band, two 10 minute exposures in another narrow band close to the Hα band (we call it the Hαoff band hereafter), seven 90 s exposures in the B band, and four 30 s exposures in the I band. The Hα filter used is the CTIO filter 6649–76 (\( \lambda_{\text{cen}} = 6650 \text{ Å}, \text{FWHM} = 77 \text{ Å} \)), as the redshifted Hα line of ESO 137-001 is centered at 6664 Å. The Hαoff filter used is the CTIO filter 6520–76 (\( \lambda_{\text{cen}} = 6530 \text{ Å}, \text{FWHM} = 71 \text{ Å} \)). The bandwidths of the two narrowband filters overlap little (at 6590 Å, the transmission of the 6649–76 filter is 4.8%, while that of the 6520–76 filter is 2.6%). Both narrowband filters are 2 inches × 2 inches (0.05 m × 0.05 m), so the non-vignetted field is only \( \sim 3.6′′ \times 3.5′′ \). Dithers of 15′′–30′′ were made between exposures. During the second half of 2006, the triplet lens of the focal reducer in SOI became partially unbounded, which caused the photometry to be uncertain to \( \sim 0.2 \text{ mag} \) from the field center to the corners. The lens of SOI was repaired in the beginning of 2007, so the photometry accuracy was recovered before our 2007 run. In this work, we use only the 2007 data in the analysis. Nevertheless, we examined the emission-line objects (see the definition and discussion in § 3) in the 2006 data (which had better seeing). All 29 emission-line objects selected from the 2007 data (§ 3) are confirmed in the 2006 data, although several of them are close to the guider in the 2006 data, so their fluxes are reduced.

Each image was reduced using the standard procedures with the IRAF MSCRED package. The pixels were binned 2 × 2, for a scale of 0.154″ pixel\(^{-1}\). The fringing on the I-band images was subtracted with the standard fringe frames. Dome flats were used. The US Naval Observatory (USNO) A2.0 catalog was used for the WCS alignment, which was done with WCSTools. Spectrophotometric standards are LTT 4364 and EG 274 (Hamuy et al. 1994). Ten standard stars in two fields (PG 1047 and RU 149) in the B, V, R, and I bands were also observed at air masses of 1.1–1.8. ESO 137-001 is near the Galactic plane (\( l = 325.25′′, b = -6.97′′ \)), so the Galactic extinction is substantial. The Galactic extinction at the B, I, Hα, and Hαoff bands is 0.89, 0.40, 0.554, and 0.568 mag, respectively, as derived from the Galactic extinction law of Cardelli et al. (1989) for \( E(B-V) = 0.207 \text{ mag} \) (from NED). As ESO 137-001 is not far from the Galactic center, the uncertainties of the Galactic extinction may not be small, but our conclusions of this paper are hardly affected.

2.2. CTIO Spectroscopic Observations

Spectroscopic observations of ESO 137-001 were conducted with the R-C spectrograph on the 1.5 m telescope at CTIO, operated by the Small and Moderate Aperture Research Telescope System (SMARTS) Consortium. Two service observations were made on 2007 June 20 and 21, using the 47/1b and 26/1a grating setups, respectively. The 26/1a setup covers a wavelength range of 3660–5440 Å with a dispersion of 1.5 Å pixel\(^{-1}\). The spectral resolution is \( \sim 4.3 \text{ Å} \). The 47/1b setup covers a wavelength range of 5652–6972 Å with a dispersion of 1.1 Å pixel\(^{-1}\). The spectral resolution is \( \sim 3.1 \text{ Å} \). The slit is always aligned east-west, with a length of \( \sim 5′′ \) and a width of \( 3′′ \). The pixel scale on the CCD is 1.3′′ pixel\(^{-1}\), and the best instrumental spatial seeing for the R-C spectrograph is only \( \sim 3.5′′ \). For the 26/1a observation (1.22–1.37 air mass), the slit was set across ESO 137-001’s center. Five exposures (20 minutes each) were made in the 26/1a run, and we combined them. The 47/1b run on 2007 June 20 (1.60–1.91 air mass) was composed of three exposures (25 minutes each). The slit was moved by several arcseconds in the north-south direction between exposures by mistake, although it was requested to be in a fixed position that was the same as the one for the 26/1a observations. Thus, we analyzed the three exposures separately. The pattern of the stellar spectra on the CCD (through the long slit) allows us to recover the slit positions. Spectroscopic standards were observed at each night: LTT 4364 for the 26/1a run and Feige 110 for the 47/1b run. As these observations of the standards used a 2′′ slit, absolute flux calibration is impossible, but the analysis of the emission line ratios should not be affected.

3. EMISSION-LINE OBJECTS

3.1. Selection of Emission-Line Objects

With data in two narrow bands (Hα and Hαoff) and two broad bands (B and I), we derived color-color and color-magnitude relations for sources in the field covered by all data (3.42′ × 3.88′ around ESO 137-001, shown by the dotted box in Fig. 16). Sextractor 2.5.0 was used to measure photometry and color. The Hα and Hαoff magnitudes are AB magnitudes as defined in Hamuy et al. (1994) and are calibrated with the data of EG 274 and LTT 4364. Galactic extinction has been corrected in all bands. In the \( \text{Hα} - \text{Hαoff} \) versus \( \text{Hα} - I \) map (Fig. 2), over 97% of the 1708 sources in the field are Galactic stars with little excess or decrement emission in the Hα filter. The \( \text{Hα} - \text{Hαoff} \) histogram peaks at approximately \( -0.02 \text{ mag} \), and the typical 1 σ dispersion is \( \sim 0.15 \text{ mag} \). The \( \text{Hα} - I \) histogram peaks at \( -0.46 \text{ mag} \) and is skewed to higher color values. The 1 σ dispersion on the lower color side is \( \sim 0.22 \text{ mag} \). Besides these stars, there are about 30 sources that are especially bright in the Hα band and occupy a different region in the color-color map. In this work, we selected 29 emission-line objects with the following conservative criteria: \( \text{Hα} - \text{Hαoff} < -0.7 \text{ mag} \) and \( \text{Hα} - I < -0.2 \text{ mag} \). These emission-line objects have equivalent widths (EWs) of \( 84–758 \text{ Å} \) (we adopted the definition of EW used in Gavazzi et al. 2006). Their positions, as shown in Figure 1b, are all down-stream of the galaxy and in or around the X-ray tail. If we relax the criteria to \( \text{Hα} - \text{Hαoff} < -0.5 \text{ mag} \) and \( \text{Hα} - I < 0.25 \text{ mag} \), six additional sources are selected, and they are also in or around the X-ray tail (Fig. 1b).
The Hα versus Hα - I relation is also shown in Figure 2. After correcting the atmospheric and Galactic extinction, the fluxes of these emission-line objects range from $1.5 \times 10^{-16}$ to $4.0 \times 10^{-14}$ ergs s$^{-1}$ cm$^{-2}$ (no correction for intrinsic extinction). We also derived the $B - I$ color for sources in the field. As some emission-line objects are not detected in the B and I bands, the $B - I$ color can be constrained only for 17 emission-line objects (Fig. 2). The emission-line objects are generally bluer than the galaxy (without correction for intrinsic extinction) and the Galactic stars. The $B - I$ colors of the Galactic stars span the range from M type (3.6–5.1 mag) to A type (0–0.4 mag). As the Galactic reddening (0.49 mag) was applied on all sources, the actual separation between the $B - I$ colors of emission-line objects and those of the Galactic stars will be wider if a smaller Galactic extinction applies on stars and if some amount of intrinsic extinction is applied for emission-line objects. Therefore, these emission-line objects are blue, and a small amount of intrinsic extinction can drive their colors to those of pure O/B star clusters.

3.2. What Are They?

What is the nature of these emission-line objects? They cannot be Galactic Hα emitters, as the required velocity ($2600–5300$ km s$^{-1}$) is too high. The other emission line close to the Hα filter band is [S ii] $\lambda$6716 (which generally has a small EW). However, a velocity of less than $1600$ km s$^{-1}$ is required to put the [S ii] line in the Hα filter band, which is also too large for Galactic objects. Thus, these emission-line objects are extragalactic. Besides being Hα emitters in A3627, these objects could also be [O iii] $\lambda$5007 emitters at $z \sim 0.33$, Hβ emitters at $z \sim 0.37$, [O ii] $\lambda$3727 emitters at $z \sim 0.78$, and Lyα emitters at $z \sim 4.47$. We have examined the expected number density of these background objects in the following two ways.

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**Figure 2**

*Top left:* Hα - Hα$_{off}$ vs. Hα - I for 1708 sources detected in the Hα band in the field ($3.42' \times 3.88'$, shown in Fig. 1b). Both the Hα and the Hα$_{off}$ fluxes include continuum. Over 97% of them are Galactic stars with Hα - Hα$_{off}$ colors close to zero. We define 29 emission-line objects (red) as sources with Hα - I < -0.2 mag and Hα - Hα$_{off}$ < -0.7 mag (limiting values are shown by the dotted lines). The Hα and Hα$_{off}$ magnitudes are AB magnitudes (Hamuy et al. 1994). We have corrected the Galactic extinction for all sources (including Galactic stars; 0.15 mag reddening for the Hα - I color), but no correction on the intrinsic extinction associated with ESO 137-001 has been applied (as is also the case for the next three plots). The purple six-pointed star marks the position of ESO 137-001’s central region, where the giant Hα nebula is, measured within a 3′ × 6′ (semi-axes) ellipse centered on the Hα peak (also shown in the next three plots). If we relax the selection criteria (see § 3.1), six more candidate emission-line objects are selected (cyan). *Top right:* Hα magnitude vs. Hα - I color. *Bottom left:* Hα - Hα$_{off}$ color vs. B - I color for sources for which the B - I color can be constrained. The emission-line objects appear to be blue, and most of them are bluer than ESO 137-001’s core (no correction on the intrinsic extinction). The Galactic reddening for the B - I color (0.49 mag) has been applied to all sources. With a small amount of intrinsic extinction, the B - I colors of emission-line objects are close to those for pure O/B stars ($-0.2$ to $-0.8$ mag). *Bottom right:* Hα$_{off}$ magnitude vs. Hα$_{off}$ - I color for sources detected in the Hα$_{off}$ band. There are no emission-line objects detected in the Hα$_{off}$ band that have Hα$_{off}$ - I < -0.2 mag. Moreover, no objects are detected with Hα$_{off}$ - Hα < -0.5 mag and Hα$_{off}$ - I < 0.25 mag.
First, we can examine the H$_\alpha$-off frame in the same way as we did for the H$_\alpha$ frame to select emission-line objects in the H$_\alpha$-off band (or sources with a large H$_\alpha$ − H$_\alpha$-off color). Both narrow-band filters have a very similar transmission and bandwidth. The difference in their central wavelength is small. Thus, we expect that the number of background emission-line objects detected in the two narrow bands should be similar. H$_\alpha$-off − H$_\alpha$ versus H$_\alpha$-off − I and H$_\alpha$-off versus H$_\alpha$-off − I maps (shown in Fig. 2) are derived for sources detected in the H$_\alpha$-off band. The same criteria used to select emission-line objects in the H$_\alpha$ band were applied (with just the change from H$_\alpha$ magnitude to H$_\alpha$-off magnitude). No emission-line objects have been found in the H$_\alpha$-off band, even though the loose criteria are applied (H$_\alpha$-off − H$_\alpha$ < −0.5 mag and H$_\alpha$-off − I < 0.25 mag). In fact, the H$_\alpha$-off exposure is deep enough to detect the faintest emission-line object in the H$_\alpha$ band, if a similar object is present in the H$_\alpha$-off frame. This single self-test already demonstrates that the expected number of background emission-line objects is very small.

Second, we examined the number density of emission-line objects from the Large Area Ly$_\alpha$ survey at z ~ 4.5 (Malhotra & Rhoads 2002), as they used the narrowband filters with similar central wavelengths and bandwidths (~80 Å) to ours. Their covered field is 0.72 deg$^2$, and the achieved sensitivity is about 5 times deeper than ours. In three nonoverlapping H$_\alpha$ filters (the central one has the same central wavelength as our H$_\alpha$ filter), 157 Ly$_\alpha$ candidates (with EW > 80 Å and without B-band detection) were detected. The size of our field is 3.42' × 3.88'. Thus, the expected number of emission-line objects selected in Malhotra & Rhoads (2002) is ~0.02 in our field (adjusted to our flux limit by assuming a power index of −1.6 for the luminosity function; Malhotra & Rhoads 2002). Cortese et al. (2004) examined ~2.5 deg$^2$ H$_\alpha$ frames of the Virgo Cluster (λ$_{cen}$ = 6574 Å; Δλ = 95 Å) obtained at the Isaac Newton Telescope. Six emission-line objects were detected (for a H$_\alpha$ flux limit of about 6 times shallower than the faintest emission-line object in our sample), and their follow-up spectroscopic observations showed that five of them were [O iii] λ5007 emitters at z ~ 0.31. If we take their number as the number density of z ~ 0.33 [O iii] λ5007 emitters at high luminosity and apply a luminosity function with a power index of −1.4 (e.g., Pascual et al. 2001), the expected number of [O iii] emitters in our whole field is ~0.09. For our line flux limit (≥10$^{16}$ ergs s$^{-1}$ cm$^{-2}$), the combined number density of the Hβ and the [O iii] λ3727 emitters is at most comparable to that of [O iii] λ5007 emitters (e.g., Pascual et al., 2001), and these two lines generally do not have a high EW.

Therefore, the expected number of background emission-line sources is much smaller than 1 in our 3.42' × 3.88' field, and it is very likely that all 29 emission-line objects are H$_\alpha$ emitters associated with A3627. In fact, this conclusion is even stronger when we consider the spatial concentration of emission-line objects immediately downstream of ESO 137-001 and around the X-ray tail. These 35 sources are not randomly distributed in the field and relative to the galaxy. Twenty-five emission-line objects cluster in a 40′′ × 60′′ region immediately downstream of ESO 137-001, while the area of our total field is 20 times larger. In § 4.1, we further show that seven emission-line objects are observed in one or more of our CTIO 1.5 m slit spectra. The spectra strongly support the argument of H ii regions (§ 4.1), at least for these seven emission-line objects. As H$_\alpha$ emitters in A3627, they are too luminous to be intracluster planetary nebulae. The H$_\alpha$ luminosity of the faintest emission-line object in our sample is >7.2 times larger (without intrinsic extinction) than the [O iii] λ5007 luminosity of the most luminous intracluster planetary nebulae in the Virgo Cluster (Ciardullo et al. 1998), and the H$_\alpha$

![Fig. 3.—Luminosities of H ii regions, plotted against their distances to ESO 137-001’s nucleus. The data points shown with open circles are six additional sources that are included if the criteria for emission-line objects are relaxed (§4). We assumed 1 mag of intrinsic extinction for all of them. For comparison, the two isolated H ii regions in the Virgo Cluster (Gerhard et al. 2002; Cortese et al. 2004) have H$_\alpha$ luminosities of 1.3 × 10$^{37}$ ergs s$^{-1}$ and 2.9 × 10$^{38}$ ergs s$^{-1}$ (intrinsic extinction corrected).](image)

line of a planetary nebula is generally several times fainter than the [O iii] line. Thus, we conclude that they are H ii regions most likely associated with ESO 137-001 and its tail in A3627. Hereafter, we simply refer to these emission-line objects as H ii regions.

### 3.3. Properties of the H ii Regions

The properties of these H ii regions and the embedded star clusters can be estimated. The intrinsic extinction is unknown. Gerhard et al. (2002) and Cortese et al. (2004) measured ~1 mag of intrinsic extinction for two isolated H ii regions in the Virgo Cluster. We simply adopt this value for all H ii regions. The [N ii] λ6548 and λ6584 lines are in the H$_\alpha$ filter band. The [N ii] λ6584 line is close to the wing (transmission there is 65% of the value in the center). Gerhard et al. (2002) and Cortese et al. (2004) measured H$_\alpha$/([N ii] λ6548 + [N ii] λ6584) ~ 0.81 for two isolated H ii regions in the Virgo Cluster. This fraction is assumed in our analysis. The derived H$_\alpha$ luminosities of these H ii regions are plotted in Figure 3 against their distance to ESO 137-001’s nucleus. The cumulative luminosity function of these H ii regions, N(> log L) ∝ L$^{-x}$, has a slope of 0.6 ± 0.1 at L$_{H\alpha}$ > 10$^{38.3}$ ergs s$^{-1}$. With the scaling relation derived by Kennicutt (1998), SFR(M$_{\odot}$ yr$^{-1}$) = L$_{H\alpha}$/(1.26 × 10$^{41}$ ergs s$^{-1}$), the SFR in these H ii regions ranges from 0.0008 to 0.17 M$_{\odot}$ yr$^{-1}$, with a total SFR of 0.59 M$_{\odot}$ yr$^{-1}$ for the 29 H ii regions selected. If we assume an electron temperature of 10$^4$ K and case B of nebular theory, the number of ionizing photons Q(H) ranges from 9.5 × 10$^{49}$ to 2.1 × 10$^{52}$ s$^{-1}$.

We can apply the Starburst99 model (Leitherer et al. 1999) to estimate the age and the total mass of the starbursts in these H ii regions. The age of the starburst can be estimated from the ratio Q(H)/L$_B$, the ratio Q(H)/L$_I$ (e.g., Gerhard et al. 2002), or the H$_\alpha$ equivalent width, EW(H$_\alpha$). The first two estimates may only provide lower limits on the age, as the intrinsic extinction of the H ii regions in the B and I bands is unknown. EW(H$_\alpha$) is not affected by intrinsic extinction, although the uncertainties are generally large and there are only lower limits in many cases. We selected eight representative H ii regions (marked ELO1–8 in Figs. 1c and 1d) to demonstrate the range of the properties of these 29 objects.
The H$\alpha$ emission of H$\Pi$ regions fades rapidly for a single starburst and will be much fainter after the initial 10 Myr. The radial velocity difference between ESO 137-001 and A3627 is only 214 km s$^{-1}$, which implies that ESO 137-001’s infalling is almost in the plane of the sky. If we assume a velocity for ESO 137-001 that is equal to the velocity dispersion of the cluster (1600 km s$^{-1}$), ESO 137-001 travels only $\sim$16 kpc in 10 Myr. It is clear that there are no very luminous H$\Pi$ regions beyond 15 kpc from the nucleus (Fig. 3). We also examined the H$\alpha$ EW of the H$\Pi$ regions against their offset from the galaxy. There is no clear relation found, as 13 sources have only lower limits. Within 8 kpc from the nucleus, the H$\alpha$ EWs span a large range from 77 to 614 Å. In any case, the three H$\Pi$ regions at distances of 29–39 kpc in projection from the nucleus must have had star formation happening in the last $\sim$10 Myr, at least 10–15 Myr after the gas was removed from ESO 137-001. Thus, the star formation in these H$\Pi$ regions does not always start immediately after they are displaced from the galactic disk, if star formation in these H$\Pi$ regions is indeed a single burst. It is likely that more H$\Pi$ regions downstream of ESO 137-001 are yet to form and that many H$\Pi$ regions may have already faded in or around the tail. We discuss the population of the H$\Pi$ regions more in § 6.

4. THE OPTICAL PROPERTIES OF ESO 137-001

4.1. The Spectroscopic Properties

The spectroscopic properties of the central emission nebula of ESO 137-001 are examined with the CTIO 1.5 m spectra. The slit positions are recovered from the stellar spectra on slits, and they are shown in Figure 4. The first slit of the 47/Ib observations misses the central emission nebula of the galaxy. The stellar spectrum at this offset position is too faint to be studied with this single exposure, while a nearby star (close to source “a” in Fig. 4; see also Fig. 1) is several times brighter. The third slit of the 47/Ib observations covers the H$\alpha$ peak of ESO 137-001, and the resulting spectrum is the brightest. The spectra of ESO 137-001’s central part are shown in Figure 5, from both the combined 26/Ia exposures and the third 47/Ib exposure. The measured velocity with the IRAF RVSAO package is $4667 \pm 135$ km s$^{-1}$ from the 26/Ia spectrum and $4640 \pm 20$ km s$^{-1}$ from the third 47/Ib spectrum, which is consistent with the value of $4630 \pm 58$ km s$^{-1}$ measured by Woudt et al. (1999). As shown in Figure 5, many line ratios can be determined. However, the 26/Ia and 47/Ib spectra were taken at different nights and at different positions. It is also impossible to do absolute flux calibration for these spectra. Therefore, we restrict our line ratio analysis only to lines in the same wavelength ranges (26/Ia or 47/Ib), which makes it impossible to apply the usual method used to constrain the intrinsic reddening with the H$\alpha$/H$\beta$ ratio. Instead, we use the H$\gamma$/H$\beta$ ratio to constrain the intrinsic reddening. The theoretical value

| ID$^a$ | $L_{H\alpha}^{b}$ | $Q(H\beta)^{c}$ | $M_{g}^{d}$ | $M_{f}^{e}$ | $EW(H\alpha)^{f}$ | Age$^{g}$ | Mass$^{h}$ | $N(O)^{b}$ |
|-------|----------------|----------------|------------|------------|----------------|--------|----------|--------|
| 1...... | 21.0 | 21.0 | $-15.29$ | $-16.76$ | 138 | 3.4, 5.4, 6.0, 6.0 | 38 | 89 |
| 2...... | 8.6 | 8.5 | $-13.62$ | $-13.82$ | 614 | 2.7, 2.3, 4.7, 4.7 | 5.3 | 20 |
| 3...... | 6.8 | 6.6 | $-13.32$ | $-13.92$ | 437 | 2.6, 3.5, 4.8, 4.8 | 5.9 | 21 |
| 4...... | 1.4 | 1.4 | $-13.39$ | $-14.17$ | 68 | 5.0, 5.7, 6.7, 6.5 | 4.6 | 7.7 |
| 5...... | 1.0 | 0.99 | $-12.00$ | $-12.42$ | 281 | 3.4, 4.7, 5.1, 5.0 | 0.95 | 3.4 |
| 6...... | 0.096 | 0.095 | $-10.48$ | $-11.02$ | $>90$ | $<5.0, <5.4, <6.3, 3.0$ | 0.019 | 0.07 |
| 7...... | 1.3 | 1.3 | $-11.28$ | $-11.94$ | $>320$ | 2.3, $<3.4, <5.0, 3.5$ | 0.43 | 1.9 |
| 8...... | 0.10 | 0.10 | $-10.59$ | $-11.14$ | $>95$ | $<5.0, <5.5, <6.3, 5.0$ | 0.096 | 0.34 |

$^a$ Source ID (see Figs. 1c and 1d).
$^b$ We assume an intrinsic extinction of 1 mag (see § 3.3 for more detail).
$^c$ The number of H-ionizing photons estimated from $L_{H\alpha}$.
$^d$ Absolute magnitudes without correction on the intrinsic extinction.
$^e$ The equivalent width of the H$\alpha$ line, if we assume an [N ii] fraction of 19% (see § 3.3).
$^f$ The age estimated from $Q(H\beta)/L_{\beta}$, $Q(H\beta)/L_{H\alpha}$, and EW(H$\alpha$), respectively, whereas the age chosen to estimate the next two properties. We generally use the age derived from EW(H$\alpha$) if it is well determined, as EW(H$\alpha$) is not affected by intrinsic extinction. Different ages for the similar objects ELO6 and ELO8 are chosen to demonstrate the change of the total mass and the number of O stars with the choice of the starburst age.
$^g$ The total mass in the instantaneous starburst estimated from Starburst99.
$^h$ The number of O stars estimated from Starburst99.

ELO1 is the brightest and the only resolved one (with a radius of $\sim$0.6 kpc). ELO2 and ELO3 are the next two most luminous ones. ELO4 is the one with the lowest value of EW(H$\alpha$). ELO5 is only $\sim0.4^\circ$ offset from the brightest Chandra hard X-ray point source in the tail (P1 in S06). The equivalent width of the H$\alpha$ line, if we assume an [N ii] fraction of 19% (see § 3.3). The first three values are estimated from $Q(H\beta)/L_{\beta}$, $Q(H\beta)/L_{H\alpha}$, and EW(H$\alpha$), respectively, whereas the age chosen to estimate the next two properties. We generally use the age derived from EW(H$\alpha$) if it is well determined, as EW(H$\alpha$) is not affected by intrinsic extinction. Different ages for the similar objects ELO6 and ELO8 are chosen to demonstrate the change of the total mass and the number of O stars with the choice of the starburst age.
for pure recombination is taken from Osterbrock (1989): 0.468 for $10^4$ K gas (case B) at $n_e = 10^2$ cm$^{-3}$. The line ratio measured is 0.35 after the correction for the Galactic reddening. Using the Galactic extinction curve from Cardelli et al. (1989) and assuming that $R_V = A_V/E(B-V) = 3.1$, we derive $A_V = 1.7$ mag for the intrinsic extinction along ESO 137-001’s core. The corresponding intrinsic extinction for the H$\alpha$ line is 1.4 mag, which is consistent with the typical extinction of the H$\alpha$ line for nearby spiral galaxies (0.5–1.8 mag; e.g., Kennicutt 1983) and the likely near–edge-on orientation of the galaxy (see § 5). Therefore, this amount of intrinsic extinction has been applied to the line ratio analysis in this paper.

The gas properties can be determined with the emission line ratios. We derived various line ratios from the combined 26/Ia...
spectrum and the third 47/1b spectrum, as their emission comes from similar regions of the galaxy (Fig. 4). We caution that the flux calibration at the blue end of the spectrum is more vulnerable to the flat-field correction, so the error of the [O II] flux is larger than are those of other strong emission lines. The [S II] λ6716/ [S II] λ6731 ratio is ~1.38, which is typical for [O II] regions and is comparable to the low-density limit of 1.35 (van Zee et al. 1998). The strong [O II] line compared to the [O III] lines suggests a low ionization parameter of the gas. We derived values of log([O II] λ6300/Hα) ≤ −1.65, log([O II] λ5007/[O III]) = −1.39, log([N II] λ6584/Hα) = −0.42, log((S II) λ6716, 6731/Hα) = 0.39, and log([O II] λ5007/Hβ) = −0.51. All these ratios indicate that the central emission nebula of ESO 137-001 resembles a typical giant H II region (Figs. 4 and 5 of Kewley et al. 2006). The low [O II] λ6300/Hα ratio implies that any central AGN, if present, is very weak, which is consistent with the X-ray nondetection of the nucleus (a 3σ limit of 5 × 10^39 ergs s^{-1} in the 0.5–10 keV band).

The gas metallicity can be estimated from several emission line ratios (e.g., Kewley & Dopita 2002), but these line ratios also depend on the ionization parameter. The ionization parameter can be estimated from the [O II] λ5007/[O III] ratio, 0.041, which implies an ionization parameter (q) of ≤ 10^5 cm s^{-1} for a gas metallicity of <2.0 times solar (Kewley & Dopita 2002). We then estimate the gas metallicity from the following line ratios for q ≤ 10^5 cm s^{-1} (Kewley & Dopita 2002):

1. log([N II] λ6584/[S II] λ6716, 6731) = 0.155, which implies that log(O/H) + 12 = 8.75–8.95.
2. log([O II] λ3727/[O II] λ4959, 5007)/Hβ = 0.90, which implies that log(O/H) + 12 = 8.05–8.20 or ~8.65.
3. log([N II] λ6584/Hα) = −0.44, which implies that log(O/H) + 12 = 8.73 or 9.35.
4. log([O II] λ6300/Hα) = −0.84, which implies that log(O/H) + 12 = 8.62–8.75.

As the line fluxes of [N II] and [O II] come from different observations, their ratio is estimated by multiplying the three line ratios [N II] λ6584/Hα, Hα/Hβ, and Hβ/O II]. For the Hα/Hβ ratio, the theoretical value of 2.86 is used for case B recombination at 10^4 K and n_0 ~ 100 cm^{-3} (Osterbrock 1989). In spite of uncertainties, we find that log(O/H) + 12 ~ 8.7 (0.6 times solar) is consistent with all estimates.

As shown in Figure 4, seven emission-line objects are also in one or more of the slit spectra. A large part of ELO1’s emission is in the 26/1a spectra. However, the best instrumental spatial seeing for the spectrograph is ~3.5″ (2.7 pixels). Since both ELO1 and the Hα core of ESO 137-001 are extended (Fig. 1) and their peaks are only 4.6″ apart, their lines will be blended in the spectra. Nevertheless, we indeed observe extension of the Hβ, [O II] λ3727, and [O II] λ5007 toward the direction of ELO1 (upward on the CCD plane; Fig. 4). The scale of the extension is consistent with the position of ELO1.

The other six emission-line objects only appear as a single line in each spectrum because their continua are very weak. Although a single line detection does not determine their redshifts, the following arguments support the proposition that at least the bright ones among them are H II regions. First, if we stack all three of the two-dimensional (2D) spectra shown in Figure 4, we detect significant [N II] λ6548, 6584 emission at ~5 σ. Second, the centroids of these lines are only <3 A (137 km s^{-1}) higher than that of the Hα line of the galaxy. Third, if the detected line is either [O III] λ5007 or Hβ at higher redshifts, we expect to find a significant Hβ or [O III] λ5007 line also in the 47/1b spectra.

From the usual [O II] λ5007/Hβ ratio (Kewley et al. 2006), however, they are not detected in either a single exposure or the stacked exposure. Good-quality spectra of these emission-line objects would require a large telescope.

4.2. The Hα and Broadband Images

The photometric properties of ESO 137-001 are also studied. As shown in Figure 1, the galaxy may have a distorted inner disk or bar within a 1 kpc radius. A dust lane is also significantly detected in all four bands at 0.5 kpc to the south of the nucleus. However, detail around the nucleus can only be obtained with Hubble Space Telescope (HST) imaging. The morphological type of ESO 137-001 (e.g., from Sb to Sd) is also unclear. Downstream in the B- and I-band images, some substructures are detected to ~6 kpc from the nucleus, including two blue streams (Fig. 1g). Interestingly, these structures all have nearby emission-line objects. Armlike features are also detected to the north (~35″ from the nucleus) and the south (~26″ from the nucleus). To quantitatively examine the optical light distribution of ESO 137-001, we measured surface brightness profiles along the minor axis and the major axis (Fig. 6). Although we estimated the intrinsic reddening around the galactic center in § 4.1, the intrinsic reddening outside the Hα emission nebula is unknown and may be smaller. Thus, we elect not to correct for the intrinsic extinction for these profiles. The Hα emission is very asymmetric along the minor axis because of the H II regions and the Hα tail downstream of the galaxy. The net Hα emission is truncated sharply upstream at ~0.9 kpc from the nucleus. The Hα emission is much more symmetric along the major axis, and the net Hα emission is truncated sharply at ~1.5 kpc from the nucleus. In the optical, the galaxy is composed of at least two components (Fig. 6). The bright inner component extends to ~1.9 kpc in radius along the major axis and to ~1.2 kpc in radius along the minor axis. Almost all of the Hα emission is within the inner component. Within the central 1.5 kpc radius, the B- and I-band light distributions have multiple peaks. The outer component can be fitted with an exponential profile, and the derived scale height is ~6″ along the minor axis and ~12″ along the major axis (see the caption of Fig. 6). The light distribution is a little more extended in the north compared to that in the south (Fig. 6).

We also measured the light profiles in elliptical annuli centered on the Hα peak (see Fig. 6). Again, the light profiles at a = 7″–32″ (where a is the semimajor axis) can be fitted with an exponential profile with a scale height of ~9.5″, while fits with the de Vaucouleurs 1/4 law overestimate the emission at a > 25″. Although the measured light profiles (without correction on the intrinsic reddening) imply little change of the B − I color with a, the known intrinsic reddening in the central Hα nebula implies that the B − I color is 1.2 mag bluer there. This blue and bright core may be a central bulge in formation. The orientation of ESO 137-001’s disk can be estimated from the classical Hubble formula. If we assume an axis ratio of ~2 and a morphological type from Sb to Sd, the estimated angle between the line of sight and the disk plane is 26°–29°. Thus, the putative disk is viewed close to edge-on.

We also derived the total B- and I-band magnitudes of ESO 137-001 with the light profiles derived in elliptical annuli (Fig. 6). The total B-band magnitude measured within a 20″ × 40″ ellipse is 14.31 ± 0.08 mag (or ~2.3L in the B band), after correcting the atmospheric and Galactic extinction. This value can be compared with the B magnitude listed on HyperLeda, which is

\[ \text{See http://leda.univ-lyon1.fr/leda/param/incl.html.} \]
14.05 ± 0.23 mag from the ESO survey. Our images are deeper and allow much better masking of Galactic stars, as some of them are very close to the nucleus (Fig. 1). The total $I$-band magnitude measured in the same aperture is 13.20 ± 0.07 mag, after correcting the atmospheric and Galactic extinction. The half-light size of the galaxy is also estimated from the light profiles measured in elliptical annuli: a 14.5′′ (4.45 kpc) semimajor axis in the $B$ band and a 14.0′′ (4.30 kpc) semimajor axis in the $I$ band. The Two Micron All Sky Survey (2MASS) $K_s$ total magnitude is 12.163 mag after correction for the Galactic extinction (0.076 mag). The intrinsic reddening measured for the Hα emission nebula would imply a corrected $B - K_s$ color of $\sim$0, although the real averaged value should be higher, as the regions outside of the Hα emission nebula may have smaller intrinsic extinction. In any case, the $B - K_s$ color of ESO 137-001 is much bluer than that of a typical late-type galaxy ($\sim$2–3.5; Jarrett 2000). The galaxy is way off the red sequence of galaxies in clusters and is in the so-called blue cloud in the cluster color-magnitude relation. The $K_s$-band absolute magnitude is $-21.97$ mag. Bell et al. (2003) determined the local $K_s$-band luminosity function and found an absolute magnitude of $-23.97$ mag for an $L_*$ galaxy (with early-type and late-type galaxies mixed, adjusted to the cosmology we used). Therefore, ESO 137-001 is a 0.16$L_*$ galaxy in the $K_s$ band. The total stellar mass of ESO 137-001 can also be estimated. The mass-to-light ratios in the $I$ and $K_s$ bands can be estimated from the relations derived in Bell & De Jong (2001): $M/L_I = 0.59 (M/L_I)_0$ and $M/L_{K_s} = 0.35 (M/L_{K_s})_0$ (using the function for the $K$ band) for $B - I = 1$ mag. The resulting stellar mass of ESO 137-001 is $4.9 \times 10^9 M_\odot$ from $L_I$ and $4.6 \times 10^9 M_\odot$ from $L_{K_s}$. The total stellar mass will be smaller if a correction for the intrinsic reddening is made. For example, for an intrinsic reddening of 0.5 mag for the $B - I$ color, the total stellar mass of ESO 137-001 will be one-third smaller. Bell et al. (2003) also determined the $M_\star$ of the local stellar mass function: $M_\star = 8.0 \times 10^{10} M_\odot$. Therefore, although ESO 137-001 is not a small galaxy, it is blue and has a low stellar mass ($\sim 0.05 M_\star$).

The net Hα emission of ESO 137-001 was also studied. The continuum emission in the Hα image is determined from the H offset frame, and the scaling factor was determined to account for all emission of stars in the Hα image (or Hα - Hα offset = 0; Fig. 2). The net Hα image is shown in Figures 1c and 1d. The net Hα flux is also measured. The calibration sources LTT 4364 and EG 274 have nearly flat spectra within the Hα filter, while the net narrowband-image of ESO 137-001 is composed of three narrow lines. We can correct for this spectral difference and subtract the [N II] flux with the CTIO spectrum (§ 4.1) and the transmission curve of the Hα filter. The Hα and the [N II] λ6548, 6584 lines can be approximated by three Gaussians with values of $\sigma$ of $\sim$3 Å. Their flux ratios are known from the CTIO data. Thus, the conversion factor from the count rate to flux can be derived. The flux is first measured in an elliptical aperture with a 3′′ semimajor axis and a 5′′ semimajor axis, centered on the Hα peak (Fig. 6), that encloses almost all the emission of the central nebula. The Hα EW is 50 Å, which can be compared with the Hα EW derived from the CTIO spectra (26 Å from the second slit position; 63 Å from the third slit position). With an intrinsic extinction of 1.4 mag (§ 4.1), the flux is $2.7 \times 10^{-13}$ erg s$^{-1}$ cm$^{-2}$ and the luminosity is $1.5 \times 10^{41}$ ergs s$^{-1}$. The total Hα luminosity of ESO 137-001, measured in a rectangular aperture (20′′ × 26′′, shown in Fig. 1d, including the Hα region ELO1 and several others), is $2.5 \times 10^{41}$ ergs s$^{-1}$ (still assuming 1.4 mag intrinsic extinction). With the scaling relation by Kennicutt (1998), the current SFR in the galaxy is $\sim 2 M_\odot$ yr$^{-1}$.

5. THE Hα TAIL

The Hα tail behind ESO 137-001 is significant for the first 1′ from the nucleus, even without continuum subtraction (Fig. 1).
Nevertheless, the high density of the foreground stars makes the detection of faint, diffuse Hα emission not easy in this region. In our analysis, bright stars are masked and the rescaled Hα eff image is subtracted. The net Hα image shows a tail to at least 2.2′ (40 kpc) from the galaxy. We note that the end of the X-ray tail is close to the brightest star in the field, which makes detection of faint, diffuse Hα emission very difficult there. The width of the Hα tail ranges from 3 to 4 kpc. The Hα tail aligns with the X-ray tail very well, and both of them are brighter in the first 1 arcsec (40 kpc) from the galaxy. We note that the end of the X-ray tail is somewhat twisted, the rms electron density in the tail is 4 × 105 e cm−2, and the total luminosity is 2.4 × 1040 ergs s−1 (with the same conversion factor used for the Hα emission of the galaxy in § 4.2). The Hα surface brightness in the tail ranges from 7.4 × 10−17 ergs s−1 cm−2 arcsec−2 near the galaxy to 1.6 × 10−17 ergs s−1 cm−2 arcsec−2 in the faint region, with an average of 2.8 × 10−17 ergs s−1 cm−2 arcsec−2. This average surface brightness is similar to that of the Hα tail of D100 in the Coma Cluster ([0.5–4] × 10−17 ergs s−1 cm−2 arcsec−2; Yagi et al. 2007) and 5–10 times higher than those of the Hα tails behind two irregular galaxies in A1367 (Gavazzi et al. 2001). In Coma and A1367, the surface density of foreground stars is a lot smaller, which permits detection of faint Hα features. We follow Yagi et al. (2007) to estimate the mass of the Hα tail. If we assume a cylinder with a 3.5 kpc diameter and a 40 kpc length (note that the tail is somewhat twisted), the rms electron density in the tail is ~0.045 cm−3. The total mass is then 5 × 106 M⊙, a filling factor of unity. This amount of mass for 10^4 K gas in the tail is similar to the X-ray gas mass of the tail in the same portion, which is ~6 × 10^6 M⊙ from S06. However, both the 10^4 K gas and the 10^7 K gas in the tail can be very clumpy. If the filling factor for the Hα-emitting gas is 0.05, the total mass of the Hα tail reduces to 10^6 M⊙. Nevertheless, the stripped ISM in the tail accounts for a significant portion of the original ISM in the galaxy. The tail may also have a cooler gas component. ESO 137-001 was undetected in the Hα observations with ATCA by Vollmer et al. (2001b). However, the limit, ~10^6 M⊙, is rather high, largely because of the nearby (14.5 kpc away) bright radio galaxy PKS 1610–60. Future more sensitive radio Hα and infrared observations are required to better quantify the ISM content in the galaxy and in the tail.

6. DISCUSSION

6.1. The Formation of H ii Regions in the Halo and the Tail

Our observations reveal at least 29 H ii regions, all of which are downstream of ESO 137-001. Interestingly, the H ii regions closest to the galactic disk form a bowlike front, with the axis close to the tail. Their projected distances from the galactic nucleus are up to 39 kpc. Most of them (if not all of them) appear away from the galactic disk plane. Similar intracluster H ii regions have been found before in the Virgo Cluster: one H ii region 21 kpc from NGC 4388’s nucleus in projection (Gerhard et al. 2002), and one H ii region 3 kpc off the disk and 6.5 kpc from NGC 4402’s nucleus in projection (Cortese et al. 2004). Both galaxies are 2–3.2 times more luminous than ESO 137-001 in the Ks band, while their isolated H ii regions have Hα luminosities of only 1.3 × 10^37 ergs s−1 and 2.9 × 10^38 ergs s−1, respectively (intrinsic extinction corrected). Intergalactic H ii regions in poorer environments have also been found (Ryan-Weber et al. 2004; Mendes de Oliveira et al. 2004). However, none of these known examples match the high number density and luminosities of the H ii regions downstream of ESO 137-001. For example, 17 H ii regions found in this work have Hα luminosities of >3 × 10^38 ergs s−1 before correction for intrinsic extinction, while only 1 region in previous work (the brightest one in Mendes de Oliveira et al. 2004) is this luminous. Moreover, five H ii regions found in this work are up to 5 times more luminous than the brightest one in Mendes de Oliveira et al. (2004). Thus, the isolated star formation activity downstream of ESO 137-001 is unprecedented.

As ESO 137-001 traverses A3627, its dark matter halo is tidally truncated by the cluster tidal field. As we do not know the characteristic velocity of the galaxy, only a crude estimate can be made. In the simulations by Gnedin (2003), a dark matter halo of a large spiral galaxy with a circular velocity of 250 km s−1 is truncated at 30 ± 6 kpc in a cluster similar to the Virgo Cluster (σradial = 660 km s−1). In smaller galaxies, the truncation radius is proportional to the circular velocity. From the Tully-Fisher relation (e.g., Gnedin et al. 2007), a disk galaxy with ESO 137-001’s stellar mass has a typical circular velocity of ~100 km s−1. Thus, we take a conservative estimate of 15 kpc for the tidal truncation radius of ESO 137-001’s dark matter halo. This estimate is also consistent with the analytical estimate by Merritt (1988). As shown in Figure 1, most of the H ii regions may still be in the halo, although three objects at 29–39 kpc from the galaxy in projection are hardly still bound. Without velocity measurements, it is unknown whether most of the H ii regions are still bound in the galactic halo. However, they may easily escape ESO 137-001’s potential via weak tidal interaction that barely affects the galactic disk. We also note that both the Hα and X-ray tails are brightest in the halo.

How did these H ii regions form? There is no indication in the optical that ESO 137-001 is merging with another galaxy. ELO1 is an emission-line source with insignificant continuum (Fig. 1 and Table 1). In fact, the merger rate in a massive cluster like A3627 should be very small, as the cluster velocity dispersion is high (σradial = 925 km s−1 for A3627). Within 100 kpc (5.3′) from the end of the X-ray tail, there are only two other galaxies identified from the Digitized Sky Survey (DSS2), 2MASS, and our data: WKK 6166 and another small galaxy without a NED identification (G1 and G2, respectively, in Fig. 1b). Neither has velocity information in the literature, and both are in the field of view of our SOAR data. In the I band, WKK 6166 is 1.6–1.9 mag fainter than ESO 137-001, depending on whether its center is blended with a star. Its radius is only ~10′, or 3.2 kpc, if it is in A3627. The other galaxy (G2 in Fig. 1b) is blended with a star. In the I band, it is 2.5–2.7 mag fainter than ESO 137-001, with a major axis extending to ~7.5′. As both galaxies are redder than ESO 137-001, with B − I colors of 1.9–2.0 mag, their stellar mass is ~30%–75% of ESO 137-001’s, from the mass-to-light ratios in Bell & De Jong (2001). However, even if these two galaxies are in A3627 and have had recent flybys with ESO 137-001 in order to tidally strip the gas clouds responsible for these H ii regions, stars should also have been tidally stripped. We would expect both stellar trails and the H ii regions to be present in both directions from ESO 137-001. On the contrary, the H ii regions are present only in a 120′ cone downstream of ESO 137-001. There are some continuum features downstream of ESO 137-001 up to 6 kpc from the nucleus (Figs. 1 and 6). However, all of them have bright H ii regions within or nearby. The upstream side of the galaxy appears to be undisturbed and free of any tidal features in both the B and I bands.
Cluster galaxies also undergo tidal interaction with the cluster potential (e.g., Gnedin 2003). Recently, Cortese et al. (2007) reported two peculiar galaxies in the massive clusters A1689 ($z = 0.18$) and A2667 ($z = 0.23$). HST images reveal stellar trails composed of bright blue knots and fainter streams behind both galaxies, extending to 20 and 75 kpc, respectively. The fainter galaxy, 131124–012040 in A1689, has a similar NIR luminosity to ESO 137-001, although the star formation in the galaxy stopped ~100 Myr ago. They argue that these features are produced through tidal interaction with the cluster potential. However, for ESO 137-001, there are no stellar trails connecting the H ii regions, at least in the current data. The detected stellar features 6 kpc downstream of the galaxy are confined around the emission-line regions and hardly extend much. Thus, it is unclear how tidal interactions could strip the clouds responsible for the current H ii regions and star clusters, yet not produce stellar trails. Future observations, such as optical spectroscopy along both axes and HST imaging, will allow us to further quantify the dynamical state of ESO 137-001 (e.g., how dynamically cool is the disk?) and the stellar diffuse emission downstream of the galaxy.

The significance of ram pressure stripping in ESO 137-001 and the bowlike front of the H ii region distribution drive us to consider another formation mechanism for these H ii regions, namely, star formation in the ram pressure–displaced ISM clouds. ESO 137-001 is undergoing a strong interaction with the surrounding ICM, judging by the compactness of the remnant Hα disk. If we assume an ambient ICM density of $6 \times 10^{-3}$ cm$^{-3}$, an ICM temperature of 6 keV (see S06), and a velocity of the galaxy of 1600 km s$^{-1}$ ($\sim \sqrt{3} \sigma_{\text{radial}}$), the thermal pressure is $0.4 \times 10^{10}$ K cm$^{-3}$, while the ram pressure is $1.1 \times 10^{5}$ K cm$^{-3}$. Therefore, the ram pressure is high enough to strip 10–100 K ISM clouds with densities up to $10^{2}$ cm$^{-3}$. H i gas will be stripped, as well as some less dense dark clouds and the outskirts of molecular clouds, even though the dense cores of molecular clouds may remain in the disk plane. Schaye (2004) found a critical surface density of $N_{\text{HI}} = (3–10) \times 10^{20}$ cm$^{-2}$ for star formation in the outer parts of the galactic disks. Some stripped dense clouds from the disk of ESO 137-001 should have higher surface densities than this critical value, even if the clouds are very clumpy. Thus, the ability of high ram pressure to displace dense clouds from the disk may affect the efficiency of star formation in the stripped ISM. The initial instantaneous stripping can be fast in a high ram pressure environment ($\approx 10$ Myr from RH05), while most materials stripped off the disk still remain bound. The subsequent evolution of the stripped ISM is complicated. Simulations (Vollmer et al. 2001a; SS01; RH05) show that a fraction of stripped materials (mainly from the outer disk; ~10% from RH05) can still be bound in the galactic halo (the “hang-up” effect) for a few hundred Myr, even in a high ram pressure environment. Some material may even fall back to the disk, while most of the stripped ISM is concentrated within several galaxay diameters downstream, in the lee of the galaxy, where the ram pressure is reduced (e.g., SS01). The details of the process rely on many factors: for example, the porosity of the ISM in the inner disk, the effective ram pressure downstream of the galaxy, the halo potential, and the efficiency of heat conduction and viscosity. Simulations (RH05; Roediger et al. 2006) also show that the wake can be very turbulent. The stripped clouds will collide with each other, which may produce shocks and trigger star formation. Moreover, being in the halo separates them from the strong stellar UV heating flux present in the disk, allowing cooling to be dominant. Thus, star formation may proceed in the halo or even in unbound clouds far away from the galaxy (e.g., ELO7 and ELO8). We note that Oosterloo et al. (2004) reported that two intergalactic H ii regions at distances of at least 100 kpc from the nearest galaxy (an elliptical galaxy) are in a massive isolated H i cloud. H ii regions in H i clouds were also reported in Stephan’s Quintet by Mendes de Oliveira et al. (2004). Thus, star formation in isolated H i clouds is plausible, although the efficiency may be low, as suggested by Oosterloo & van Gorkom (2005). This scenario can explain the spatial distribution of the H ii regions, although the details are certainly complicated. SS01 even suggested formation of dwarf galaxies by these means. We indeed note that the brightest H ii region, ELO1, has an estimated total mass of $\sim 4 \times 10^{5} M_{\odot}$. If star formation in ELO1 is still active, ELO1 may grow into a dwarf galaxy eventually. Future HST and high-resolution H i observations are required to better understand ELO1, other bright H ii regions, and the stripped ISM.

6.2. The Fate of the Isolated H ii Regions and Their Implications

The estimated ages of the H ii regions are less than ~8 Myr. The length of the X-ray tail implies that stripping has lasted for ~50 Myr (if we assume a velocity of ~1 500 km s$^{-1}$ in the plane of the sky). Thus, it is possible that many H ii regions may have already faded. Nevertheless, the long spatial distribution of the H ii regions along the tail implies that after the ISM has been stripped, the time lapse to the beginning of star formation spans a range of up to ~20 Myr or more (e.g., for ELO7 and ELO8). Contrary to ELO7 and ELO8, some luminous H ii regions (e.g., ELO1–ELO3) are only ~1.6–5 kpc from the galactic disk in projection, but their ages are comparable to those of ELO7 and ELO8 (if not longer). Their estimated ages are longer than the required time to produce the observed projected offsets. Thus, this may be the evidence that a significant part of stripped ISM from the disk can still be bound in the halo. We also explore the possibility of detecting faded H ii regions from the imaging data. The six additional emission-line regions selected with stricter criteria (Fig. 2) are certainly candidates with stronger I-band continuum. They are also close to the 29 H ii regions. The embedded star clusters are blue if the intrinsic extinction is not too high. From the Starburst99 model, we find that star clusters like those in ELO1–ELO3 should be detected in the B and I bands with our data, even at ages of 50–60 Myr. However, it is difficult to distinguish them from the various types of Galactic stars in the foreground. About 10 Myr after the initial starburst, red supergiants appear and the galactic colors are highly metallicity dependent over this period. For star clusters with metallicities larger than 0.4 times solar, Starburst99 also predicts a big increase for the B – I color at ~10 Myr for instantaneous starbursts. The B – I color can be as high as 1.7 mag in that period, which makes it difficult to select faded star clusters from Galactic stars with imaging data alone (Fig. 2). In fact, 10 non–emission-line objects with B – I < 0.8 mag (Fig. 2) are mostly bright stars, and none of them are close to the tail. Thus, faded H ii regions may be selected only through a spectroscopic survey. If formation of massive stars proceeds in the stripped ISM, high-mass X-ray binaries may form in those star clusters. The existing shallow (14 ks) Chandra observation reveals only three hard X-ray point sources in the tail ($\geq 10^{40}$ ergs s$^{-1}$ if in A3627), but both the XMM-Newton and the Chandra spectra reveal an unresolved hard component in the tail (S06). Interestingly, the brightest Chandra point source, P1 (S06), is only ~0.4″ from the putative H ii region ELO5 (Fig. 1), while the combined positional uncertainty from Chandra and the SOAR data can be up to ~0.3″. The Chandra point source P3 positionally coincides with
a red optical source \((B - I = 3.2)\) with an Hα - H_o0ff color of 0.01, which is likely a star. The Chandra point source P2 is 0.7'-0.9' from two starlike objects, but only 2.5' away from an emission-line object candidate (Fig. 1). We have a 150 ks Chandra ACIS-S observation approved for Cycle 9, which can probe the X-ray point-source distribution 20 times deeper than the existing data.

The ESO 137-001 data strongly imply a connection between stripping of the ISM and star formation in the halo and intracluster space. The stripped ISM not only contributes to the ICM, but also adds intracluster light by subsequent star formation after stripping. The total mass of starbursts in the 29 H II regions is about \(10^5 M_\odot\) (with large uncertainty from age and extinction), while the total gas mass of the Hα tail and the X-ray tail is \(\lesssim 10^6 M_\odot\) (depending on the filling factor and density variation). As many H II regions may have already faded and star formation may still proceed in the stripped ISM, the final total stellar mass formed in the halo and intracluster space should be at least several times larger than the \(10^7 M_\odot\) estimated above. As most of the H II regions may still be in the halo, it is possible that star formation in stripped ISM is more efficient in the halo than in intracluster space. For the star clusters in the halo, some of them may remain bound, while others may escape the galactic potential through tidal interactions. Thus, this single transforming galaxy, ESO 137-001, contributes over \(10^7 M_\odot\) of new stars in the halo and intracluster space through star formation in the ram pressure–displaced clouds, although it is unclear how many will end up in intracluster space. If some large star clusters are bound to the galaxy for a significant amount of time, the configuration may look like galaxy aggregates found in the Coma Cluster (Conselice & Gallagher 1998).

6.3. Hα Tail and Stripping of the Galactic ISM

There are not many cluster galaxies with known Hα tails: two irregular galaxies in the northwest of A1367 (Gavazzi et al. 2001), NGC 4388 in the Virgo Cluster (Yoshida et al. 2002, 2004), a poststarburst galaxy near the center of the Coma Cluster (Yagi et al. 2007), and several galaxies in an infalling compact group toward A1367 (Sakai et al. 2002; Gavazzi et al. 2003; Cortese et al. 2006). Both galaxies in the northwest of A1367 and the poststarburst galaxy in Coma have similar \(K_s\)-band absolute magnitudes to that of ESO 137-001 (from 0.49 mag fainter to 0.10 mag brighter), implying a similar total stellar mass to that of ESO 137-001. NGC 4388 is 1.3 mag more luminous than ESO 137-001 in the \(K_s\) band and is also larger. Both Hα tails in A1367 are suggested to be produced by ram pressure stripping, while the tidal interaction between the two galaxies may trigger star formation in both galaxies (Gavazzi et al. 2001). The Hα tail behind the galaxy D100 in Coma is remarkably narrow and straight (60 kpc x 2 kpc). It may be produced through either ram pressure stripping or from the gas of a merging dwarf (Yagi et al. 2007). The Hα filaments in the northeast of NGC 4388 are suggested to be ionized by NGC 4388’s AGN, while ram pressure stripping of the ISM provides the cool gas trail (Yoshida et al. 2004). The remarkable infalling compact group in A1367 is composed of several giant galaxies, many dwarf galaxies, and Hα-emitting knots. We note that the \(B\)-band absolute magnitude of ELO1 (before correction on the intrinsic extinction) is comparable to that of the faint dwarf galaxies in that infalling group (\(M_B = -15.3\) mag, compared to \(-15.8\) mag). Cortese et al. (2006) suggested that the rich star formation phenomena in this infalling group are triggered by tidal interactions between group members and the ram pressure by the ICM. The galaxy C153 in A2125 (\(z = 0.247\)) is another similar case (Wang et al. 2004; Owen et al. 2006), with a wide 80 kpc [O II] tail that is also likely shown in the X-rays. The galaxy has a distorted disk with substantial star formation activity, just when it is penetrating the cluster core. However, it is far more distant than all other galaxies discussed here, so the interaction cannot be studied in the same detail as others. There are no detections of X-ray tails behind the other galaxies with Hα tails in the Chandra or XMM-Newton data. There are also no reports of isolated H α regions near the two galaxies in the northwest of A1367 and D100 in Coma. The spectroscopically confirmed H II region by Gerhard et al. (2002) is north of NGC 4388 but is far away from the Hα filaments revealed by Yoshida et al. (2002). Other emission-line objects in that part of the Virgo Cluster are even farther away from the Hα filaments (Fig. 1 of Okamura et al. 2002).

How does the Hα tail of ESO 137-001 form? The net Hα image of the galaxy shows the truncation of the Hα emission on the front and the sides (Figs. 1 and 6). In fact, the leading edge of the X-ray emission in ESO 137-001 coincides positionally with the Hα front. The compactness of the remaining Hα core demonstrates the strength of the ICM wind. Compared with simulations by Roediger & Hensler (2005), over 90% of the gas in the original gas disk should have been removed from the disk, either hanging up in the halo or in the tail. Thus, ram pressure stripping should play an important role in the formation of the observed Hα tail. The stellar ionization field in the tail may be too weak to ionize the stripped cold gas to produce the observed Hα tail, at least from the current data. The positional coincidence of the Hα tail and the X-ray tail implies a connection. Can heat conduction from the surrounding ICM to the cold stripped ISM provide enough energy? Heat conduction across the embedded cold clouds is most likely saturated. We use the saturated heat conductivity derived by Cowie & McKee (1977) to estimate the inflowing heat flux. The surface area is still estimated from a cylinder with a 3.5 kpc diameter and a 40 kpc length (\(\S 5\)), although the real contact surface is almost certainly higher (e.g., for clumpy clouds). The total heat luminosity is \(4.7 \times 10^{43} \text{ ergs s}^{-1}\) for an ICM temperature of 6.5 keV and an ICM density of \(10^{-3} \text{ cm}^{-3}\). Although the energy emitted through Hα is only a small fraction of the total optical line cooling (several percent; Voit et al. 1994), there is enough heat energy for the observed Hα tail. However, heat conduction can be largely suppressed by magnetic fields at the boundaries of the clouds. It is likely that both stripping and heat conduction contribute to the observed Hα tail. Spectroscopic studies of the Hα tail, although difficult, will better clarify its nature. Radio observations are also required to study the distribution of the cold atomic and molecular gas in and behind ESO 137-001.

7. CONCLUSIONS

ESO 137-001 is a star-forming galaxy with a dramatic X-ray tail (S06). In this work, we present optical imaging and spectroscopic data of ESO 137-001 from SOAR and the CTIO 1.5 m telescopes. An Hα tail is found behind ESO 137-001, extending to at least 40 kpc from the galaxy. The Hα tail positionally coincides with the X-ray tail. We conclude that ram pressure stripping is responsible for the ISM tail, while heat conduction from the hot ICM may also contribute to the energy of the optical lines. This discovery makes ESO 137-001 the only known cluster galaxy with both an X-ray tail and an Hα tail. The Hα emission in ESO 137-001 is confined to the central ~1 kpc (radius) region. The current nuclear SFR (~1.2 \(M_\odot\) yr\(^{-1}\)) and the largely enhanced stellar continuum (after correction of intrinsic extinction) around the center imply that a galactic bulge may be building up. At least 29 emission-line objects with high Hα flux are also revealed by the data. They all spatially cluster downstream.
of the galaxy, in or around the stripped ISM tail. Those closest to the galactic disk form a bowlike front. From analysis of the Hα off frame and the estimate of the background emission-line objects, we conclude that the expected number of background objects is much less than 1 in the whole 3.43′ × 3.88′ field and that all 29 emission-line objects are very likely to be H II regions associated with ESO 137-001. The high number density and luminosities of these H II regions downstream of ESO 137-001 dwarf the previously known examples of isolated H II regions in clusters, making ESO 137-001 a dramatic example full of rich phenomena. Interestingly, one Chandra point source (an ULX with L_X > 10^{46} ergs s^{-1} if in A3627) is in the same position as an H II region. All these detections indicate significant star formation activity in the halo of ESO 137-001 and in intracluster space.

Our data imply a connection between these H II regions and the stripping of the ISM. We suggest that star formation may proceed in the stripped ISM, in both the galactic halo and the intracluster space. The star formation in the halo may have a higher efficiency, as the stripped ISM is still bound. Cooling can become dominant when the surrounding UV radiation field is much weaker than that in the disk. Collisional processes may also induce collapse of the ISM clouds. The total mass of the current starbursts in these 29 H II regions is about 10^7 M_☉. Since many H II regions and star clusters may have already faded, the total stellar mass formed in the stripped ISM may be several times higher. Therefore, stripping of the ISM not only contributes to the ICM, but also adds intracluster stellar light through subsequent star formation.

There is no reason to believe that ESO 137-001 is unique. However, its current active stage may last only for a short time (<<10^9 yr), so a large sample of cluster late-type galaxies would have to be studied to find more galaxies similar to ESO 137-001, either in X-rays or Hα. Nevertheless, the proximity of ESO 137-001 makes it a good target for the study of galaxy transformation, the evolution of stripped ISM, star formation, and X-ray binaries in the halo and the intracluster space, with the help of more data.

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