THE REMARKABLE 60 × 2 kpc OPTICAL FILAMENT ASSOCIATED WITH A POSTSTARBURST GALAXY IN THE COMA CLUSTER

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ABSTRACT

In the deep narrowband image of the Coma Cluster taken with Suprime-Cam of the Subaru Telescope, we found an extremely long and narrow (~60 × 2 kpc) Hα-emitting region associated with a poststarburst galaxy (D100). Follow-up spectroscopy shows that the region has the same redshift as D100. The surface brightness of the region is typically 25 mag (AB) arcsec⁻² in Hα, which corresponds to (0.5–4) × 10⁻¹⁷ ergs s⁻¹ cm⁻² arcsec⁻². We propose two possible explanations for the origin of the region; gas stripped off from a merged dwarf or gas stripped off from D100 by ram pressure. Either scenario meets with difficulty in fully explaining all the observed characteristics of the region.

Subject headings: galaxies: evolution — galaxies: structure

Online material: color figures

1. INTRODUCTION

Deep Hα imaging provides an opportunity to detect new faint, extended features, even in well-studied regions (e.g., Veilleux et al. 2003). In the nearby cluster Abell 1367, Gavazzi et al. (2001) found extended ionized regions associated with starburst Irr galaxies. The sizes of the regions are 75 × 8 kpc and 50 × 8 kpc. Yoshida et al. (2002) discovered another extremely extended ionized region (~35 kpc) in the Virgo Cluster, which is found to be part of a 110 × 25 kpc Hα gas region (Oosterloo & van Gorkom 2005). Veilleux et al. (2003) used a tunable filter to search for ionized gas around nearby galaxies. They found ~20 kpc complex filaments in six galaxies out of 10. Another type of elongated gas is the Magellanic Stream (hereafter MS; Mathewson et al. 1974). The MS is orbiting around our Galaxy and emitting Hα (Weiner & Williams 1996, hereafter WW96). The connection between such an ionized region and the evolution of its associated galaxy is, however, not understood.

In this paper, we report the serendipitous discovery of a long and narrow (~60 × 2 kpc) ionized region associated with a poststarburst galaxy D100 (Dressler 1980; or GMP 2910, Godwin et al. 1983) in the Coma Cluster. We assume that the distance modulus of the Coma Cluster is (m – M)₀ = 35.05 and (h₀, Ω_m, Ω_Λ) = (0.73, 0.24, 0.72) (Spergel et al. 2006). Under these assumptions, 1° corresponds to 0.474 kpc at this distance.

2. IMAGING OBSERVATION AND RESULT

We observed 34′ × 27′ region near the Coma Cluster center (α, δ) = (12h59m26s, +27°44′16″) (J2000.0) with Suprime-Cam (Miyazaki et al. 2002) at the Subaru Telescope on 2006 April 28 and 2006 May 3 UT (Table 1). We used three broadband filters, B, R, and i, and a narrowband filter (N-A-L671, hereafter NB). The NB filter is designed to observe Hα-emitting objects in the Coma Cluster at z = 0.0225 and has a bell-shaped transmission, with central wavelength 6712 Å and FWHM 120 Å. The imaging data were reduced in the standard manner. The limiting surface brightness and the point-spread function (PSF) sizes of the final image are summarized in Table 1. We adopted SA 113 (Landolt 1992) for the R- and B-band photometric standard. The photometric zero points are converted to AB magnitude, assuming the m(AB) = m(Landolt) is 0.169 and −0.140 for R and B, respectively (Fukugita et al. 1995). The flux of NB and the i band are calibrated with the spectrophotometric standard, GD 153 (Borlin et al. 1995) for NB and HZ 44 (Oke 1990) for i. The magnitudes of the stars are m(GD 153) = 13.77 (NB) and m(HZ 44) = 12.35 (i) in the AB system.

In order to create the Hα image, we subtract the scaled R-band image from the NB image, so that the residual of typical stars and galaxies should be minimal. The resulting Hα image is shown in Figure 1, together with the broad-band images. A striking feature can be seen in the Hα image: a narrow and straight ionized region reminiscent of a jet extends from the galaxy D100 to the northeast. The contour of NB surface brightness is shown in Figure 2. D100 is an Irr or Sab galaxy of magnitude Mr = 20. It is noted that the direction of the major axis of D100 is slightly different in the Hα image and the three broad-band images. Its neighbor D99 has a different velocity and is thought to be a chance overlap (Caldwell et al. 1999, hereafter C99). The third galaxy, GMP 2913, has no spectroscopic information in the literature.

We carefully surveyed archival data of D100 and found that the feature is vaguely recognized in the shallow R-band image taken at the William Herschel Telescope (WHT) in 1996 (Komiya et al. 2002) and in the R-band Subaru image taken in 2001. Bright parts are also visible in the shallow Hα image of the Universidad Complutense de Madrid survey (Pérez-González et al. 2003). This feature is therefore not transient over a timescale of ~10 yr.

3. SPECTROSCOPIC OBSERVATION AND RESULTS

The spectra of some parts of the region were taken with the Faint Object Camera and Spectrograph (Kashikawa et al. 2002)
in multiobject spectroscopy mode on 23 June 2006 UT. We used short slits whose lengths were 6′′–16′′ to obtain the spectra of bright filaments in the ionized region. The width of the slits was 0.8′′, giving the spectral resolution $R \approx 700$ with the 300B grism. We obtained eight sets of 30 minute exposures. The sky condition was not photometric. We observed HZ 44 (Oke 1990) for relative flux calibration.

The data were reduced in the standard manner, including bias subtraction, flat-fielding, and distortion correction. For wavelength calibration, we used night-sky emissions. A background sky spectrum is constructed for each exposure from spectra where no feature is detected in either our NB image or Hα image. The sky-subtracted spectra of the eight exposures are then scaled and co-added with a 3 $\sigma$ clipping. Examples of the resulting spectra are shown in Figure 3.

The redshift of D100 center (ID 01) is estimated to be $z = 0.01784$ from Hα, [N ii], and [S ii] emissions. The value is consistent with $z = 0.01776 \pm 0.00017$ of D100 itself reported by Smith et al. (2004). The vertical lines in Figure 3 indicate emission at the estimated redshift of D100. We also obtained a spectrum of neighbor galaxy, GMP 2913. The galaxy shows strong emission at the estimated redshift of D100. We also obtained a spectrum of neighbor galaxy, GMP 2913. The galaxy shows strong emission at the estimated redshift of D100. We also obtained a spectrum of neighbor galaxy, GMP 2913. The galaxy shows strong emission at the estimated redshift of D100.

The lack of any AGN sign is consistent with previous studies of this galaxy (Quillen et al. 1999 C99).

There is no sign of active galactic nucleus (AGN) activity, because the ratio of [O iii] $\lambda 5007$/Hβ is smaller than 0.49 at the center. The total mass of the ionized gas is estimated as follows. Since we have no information about inclination, we assume that the extension of the region is perpendicular to the line of sight, and it is approximated hereafter by a cylinder 60 kpc long by 1 kpc in radius. The typical Hα surface brightness of the region is $\sim 2 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ (Table 2). It corresponds to an Hα photon flux of $3 \times 10^{50}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The case B recombination coefficient at $T_e \sim 10^4$ K is $\alpha_B \sim 2.6 \times 10^{-13}$ cm$^3$ s$^{-1}$ (Bland-Hawthorn & Maloney 1999). Assuming optically thin gas and an isotropic radiation field, the emission measure of the region is estimated as $n_e^2 L \sim 5$ cm$^{-6}$ pc. We assume that the thickness of $d$ indicates that the region is physically associated with D100. Since the spectra were obtained under nonphotometric conditions, we calculate Hα flux (Table 2, col. [8]) from the NB surface brightness of the imaging data (Table 2, col. [5]), the NB filter response, and the observed spectrum.

C99 described spatially resolved spectra of D100 in detail. They reported that the galaxy has both strong emission and strong underlying Balmer absorption in the central 2′′, while only Balmer absorption is seen at 3′′ radius. Such a configuration is also seen in our Figure 1. This suggests that the central starburst was triggered shortly after star formation in the disk stopped for some reason. In our spectra, Hα absorption is seen in the regions over the core. In ID 02 spectra, which is in the emission-line region, Hβ emission is buried in strong Balmer absorption, and only [O iii] is detected. Therefore, among the values in Table, 2 we regard [N ii]/Hα and [O iii]/Hβ as upper limits and the Hα brightness as a lower limit in the regions where continuum is detected (ID 01-04).

4. CHARACTERISTICS OF THE EXTENDED REGION

A distinct characteristic of the ionized region is its morphology; it is narrow (≈ 2 kpc), long (≈ 60 kpc), and straight. The region ends at the central region of D100, and no emission is found on the opposite side (Fig. 1). The velocity field of the region is distorted and does not show any smooth global gradient, but it suggests that the region is kinematically connected to the center of D100 (Table 2). The nucleus of D100 shows starburst characteristics, and its disk shows a poststarburst feature whose age is $\sim 1$ Gyr (C99).

Bravo-Alfaro et al. (2000) observed Hα around the center of Coma, with typical thresholds of $(2–4) \times 10^{19}$ cm$^{-2}$. Although their observed region includes D100, they found no Hα feature around D100. Regarding X-ray, Finoguenov et al. (2004) presented a resolved X-ray map of the Coma Cluster center, but no feature is recognized around D100.

The total mass of the ionized gas is estimated as follows. Since we have no information about inclination, we assume that the extension of the region is perpendicular to the line of sight, and it is approximated hereafter by a cylinder 60 kpc long by 1 kpc in radius. The typical Hα surface brightness of the region is $\sim 2 \times 10^{-17}$ ergs cm$^{-2}$ s$^{-1}$ arcsec$^{-2}$ (Table 2). It corresponds to an Hα photon flux of $3 \times 10^{50}$ cm$^{-2}$ s$^{-1}$ sr$^{-1}$. The case B recombination coefficient at $T_e \sim 10^4$ K is $\alpha_B \sim 2.6 \times 10^{-13}$ cm$^3$ s$^{-1}$ (Bland-Hawthorn & Maloney 1999). Assuming optically thin gas and an isotropic radiation field, the emission measure of the region is estimated as $n_e^2 L \sim 5$ cm$^{-6}$ pc. We assume that the thickness of

![Figure 1](image1.png)  
**Fig. 1.** Left to right: Images around Mrk 60 (D99+D100 system) in $B$, $R$, $i$ and Hα ($\approx$NB $– R$). The size is 200′′ $\times$ 200′′, and east is up. In the Hα image, white represents Hα emission, and black represents Hα absorption. [See the electronic edition of the Journal for a color version of this figure.]
the region $L \sim 2$ kpc, and then the rms of the electron density is $\langle n_e \rangle \sim 0.05$ cm$^{-3}$. If the gas is totally ionized and have uniform distribution, the mass of the ionized gas is about $\pi(1 \text{ kpc}^2) \times (60 \text{ kpc}) \langle n_e \rangle m_{\text{H}} \sim 2 \times 10^8 M_\odot$. The order of the estimated mass is comparable to the order of total gas mass in a dwarf galaxy. If the ionization fraction is lower, the value is underestimated. However, if the ionization fraction is lower than 0.9, for example, the $\text{H}^+$ column density is $>3 \times 10^{19}$ cm$^{-2}$ and must have been detected in $\text{H}^+$ observations by Bravo-Alfaro et al. (2000), whose threshold is $2 \times 10^{19}$ cm$^{-2}$. We can conclude that the ionization fraction should be almost unity. If the filling factor is low, on the other hand, the total mass should be smaller. The estimated value, $\sim 2 \times 10^8 M_\odot$, is therefore the upper limit.

5. POSSIBLE EXPLANATION

At first glance, the straight morphology of the ionized region gives us the impression that it is a jet ejected from the galaxy nucleus. The lack of current AGN activity in D100 and no detection of a radio jet around D100, however, makes it difficult to interpret the ionized region as an AGN jet. In the following, we discuss possible scenarios for the origin of the extended ionized region and answer questions about (1) the origin of the gas,
(2) the mechanism that caused the long and narrow morphology, and (3) the ionization source.

5.1. Infalling Dwarf Scenario

One possibility is that the gas came from some other object than D100, either a galaxy or a gas cloud. The object would possibly be dissipated or absorbed by D100, because we cannot find any giant galaxies near the region. The neighbor dwarf, GMP 2913, is apparently not connected to the region, and therefore GMP 2913 might not be the origin of the gas. A possible candidate is a small clump seen 4 arcsec away from the center of D100 (corresponding to ID 03 spectra in Table 2 and Fig. 2), which could be a remnant core of an infalling dwarf.

In this infalling dwarf hypothesis, either ram pressure on the dwarf or tidal force by D100 could be the mechanism for forming the region. A famous example of an elongated gas cloud without stars is the MS. The width of the MS is estimated to be <3.5 kpc (WW96). The length of the MS can be calculated as ~50 kpc, from its extension in the sky (~50˚; e.g., Brüns et al. 2005) and its distance from us (~50 kpc). The size is comparable to the extended region discussed here. The total H I mass of the MS, (2–5) \times 10^8 M_\odot (Moore & Davis 1994; Putman et al. 2003b; Brüns et al. 2005), is also comparable to the estimated gas mass of the region. The mechanism that formed the MS is still under debate (e.g., Connors et al. 2006 and references therein), but the same mechanism might have worked here. WW96 reported that the brightest parts of the MS emit \sim 2 \times 10^{-17} erg cm^{-2} s^{-1} arcsec^{-2} of H_\alpha, which is comparable to the H_\alpha brightness observed for the region in this study (see Table 2). The difference is that the H_\alpha-emitting region in the MS is patchy (Putman et al. 2003a), while the region in this study has smooth and widespread H_\alpha emission (Figs. 1 and 2). The difference might be explained by a difference of the ionization source.

The ionization source of bright spots of the MS was first thought to be friction in the hot plasma of the Galactic halo (WW96). Although the mechanism is believed insufficient for the luminosity of the bright spots in the MS (Bland-Hawthorn & Maloney 1999, 2002; Bland-Hawthorn & Putman 2001), it could work effectively in a hot intracluster plasma in the Coma Cluster. Putman et al. (2003a) suggested that some bright spots in the MS, which are an order of magnitude stronger in H_\alpha, might be produced through interaction with halo debris. Similarly, the interaction with surrounding plasma in the Coma Cluster could ionize the region in this study. We can see enhanced [N ii]/H_\alpha and [O iii]/H_\beta ratios in some part of the extended emission region, which implies moderately low energy shocks of moderately metal-rich gas.

To explain the H_\alpha emission of the MS, Bland-Hawthorn & Maloney (1999) showed that escaping photons from the Galactic disk can ionize the spots. Using simple model, we checked whether escaping photons from D100 can ionize the region. The apparent size of the H_\alpha-emitting region of D100 is \sim 500 arcsec^2 = 1.2 \times 10^{-8} sr. Since the typical H_\alpha photon flux density of the extended region is 3 \times 10^{-5} cm^{-2} s^{-1} arcsec^{-2}, the total H_\alpha photon flux is 3.5 \times 10^{-5} cm^{-2} s^{-1}. Assuming the distance to the region from us to be 100 Mpc, total H_\alpha photon flux from the region is 4 \times 10^{-51} s^{-1}, if the region is cylindrical. Since most of the disk is now in the poststarburst phase, we simplify the model to require that ionizing photons be created only at the core and calculate the H_\alpha photons from a cone 60 kpc deep with a 1 kpc radius, whose opening angle is 8.7 \times 10^{-4} sr. Since the volume of a cone is 1/3 of a cylinder, the flux from the cone is 1.3 \times 10^{51} s^{-1}. Assuming spherical symmetry, the whole ionizing photon flux from the core...
is estimated as $1.9 \times 10^{55} \text{ s}^{-1}$. Following Kennicutt (1998), the star-forming rate required to ionize the region is $\sim 200 \ M_\odot \ \text{yr}^{-1}$ in D100. If there was a strong starburst at the D100 core for $\sim 2 \times 10^7 \ \text{yr}$ (60 kpc/light speed) and the core region is free from dust, the photon from the core could ionize the whole extended region.

Yet another ionizing source is EUV photons from hot plasma (Maloney & Bland-Hawthorn 2001). Maloney & Bland-Hawthorn (2001) suggested that EUV from hot gas in a cluster of galaxies can be the ionizing source of gas clouds. Such ionizing EUV is found to be strong in the Coma Cluster (Bower et al. 2004), and it is also possible that the extended region is ionized by the EUV. Any of these three possible sources or their combinations could ionize the extended region.

A possible infalling dwarf scenario is as follows. (1) A dwarf galaxy was trapped by the gravity of D100 and started to interact. (2) The gas in the D100 disk lost angular momentum and fell into the core. This stopped star formation in the disk, and the central starburst was triggered. (3) The dwarf expelled gas as a stream by the same mechanism that formed the MS. (4) The gas is orbiting around D100, or infalling into D100, and is fully ionized by some mechanism discussed above.

The problem with this scenario is the configuration of the region. The stream seems to be smoothly connected to the core, and there is no feature on the other side of the core. To reproduce such an appearance, the stream should end or be truncated just at our line of sight to D100. Moreover, as we see a straight morphology, the stream is observed edge-on. The probability of such a configuration is very low. The absence of a smooth velocity gradient is another difficulty, since such a stream is thought to have a smooth velocity gradient.

### 5.2. Ram Pressure Stripping Scenario

We should consider the other possible origin of the gas, that the gas came from the disk of D100. Under this assumption, the mechanism that formed the region would be ram pressure stripping by surrounding gas. C99 noted that D100 shows little rotation at a 121° position angle, which might imply that D100 has shallow gravitational potential. If this is the case, it would be possible to strip the central gas of D100 very far away from the galaxy by ram pressure. Two examples of ionized gas stripped by ram pressure are reported by Gavazzi et al. (2001) in Abell 1367; their sizes are $75 \times 8 \text{ kpc}$ and $50 \times 8 \text{ kpc}$. Another example is discovered by Sun et al. (2006) in A3627 as an $71 \times 8 \text{ kpc}$ X-ray tail. The ionizing source of the region could be the same as that of the infalling dwarf scenario: escaping photons from D100, a moderate internal shock, and/or EUV photons from hot plasma.

In this scenario, the formation of the region is as follows. (1) A dwarf galaxy was trapped by the gravity of D100 and started to interact. The interacting galaxy could be the neighboring GMP 2913 or a small clump near the core (ID 03). (2) The gas in the D100 disk lost angular momentum and fell into the core. This stopped star formation in the disk, and the central starburst was triggered. (3) The condensed central gas experienced ram pressure from the intracluster medium (ICM) and was stripped with disturbed velocity. (4) The gas was blown far out of the disk. This scenario explains the distorted velocity field in the region and the fact that the end of the stream is connected to the core.

One difficulty of the scenario is that the ionized region is so narrow and straight ($2 \times 60 \text{ kpc}$) compared with the examples found in previous studies (e.g., $75 \times 8 \text{ kpc}$ and $50 \times 8 \text{ kpc}$; Gavazzi et al. 2001) and simulations (e.g., Roediger et al. 2006). Bland-Hawthorn et al. (1995) suggested that intracluster plasma can confine ionized gas in the Fornax Cluster. A similar confinement process may be able to confine such a narrow ($<2 \text{ kpc}$) and long extended region in the Coma Cluster, since the surrounding hot plasma is much denser than Fornax. This scenario also requires some reason why ram pressure began to act just after D100 experienced the merger. If the infall of disk gas was induced not by the minor merger, but by the ram pressure, the coincidence would seem to be natural. Although it is known that most field poststarburst galaxies are created by merger/interaction (e.g., Zabludoff et al. 1996; Blake et al. 2004; Goto 2005 and references therein), such a ram pressure–induced poststarburst in rich clusters has also been suggested by some previous studies (Poggianti et al. 2004; Pracy et al. 2005). Currently, we do not have simulations to reproduce such a morphology of ionized gas.

We will need some additional data, such as resolved and much deep X-ray and radio data and the metallicity of the gas, to investigate the nature of the region in detail. As we set the slit along the region, spectroscopy of higher spatial resolution across the region would give us other hints about velocity structure and gas excitation, which may set constraints on gas properties and the confinement mechanism. We also require some model simulations to reproduce the morphology.

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