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Discovery of Ram-pressure Stripped Gas around an Elliptical Galaxy in Abell 2670

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Abstract

Studies of cluster galaxies are increasingly finding galaxies with spectacular one-sided tails of gas and young stars, suggestive of intense ram-pressure stripping. These so-called "jellyfish" galaxies typically have late-type morphology. In this paper, we present Multi Unit Spectroscopic Explorer (MUSE) observations of an elliptical galaxy in Abell 2670 with long tails of material visible in the optical spectra, as well as blobs with tadpole-like morphology. The spectra in the central part of the galaxy reveal a stellar component as well as ionized gas. The stellar component does not have significant rotation, while the ionized gas defines a clear star-forming gas disk. We argue, based on deep optical images of the galaxy, that the gas was most likely acquired during a past wet merger. It is possible that the star-forming blobs are also remnants of the merger. In addition, the direction and kinematics of the one-sided ionized tails, combined with the tadpole morphology of the star-forming blobs, strongly suggests that the system is undergoing ram pressure from the intracluster medium. In summary, this paper presents the discovery of a post-merger elliptical galaxy undergoing ram-pressure stripping.

Key words: galaxies: clusters: individual (Abell 2670) – galaxies: clusters: intracluster medium – galaxies: elliptical and lenticular, cD – galaxies: kinematics and dynamics – galaxies: star formation

1. Introduction

A galaxy infalling into a massive cluster halo experiences ram pressure as it moves through the intracluster medium (ICM; Gunn & Gott 1972). The ram pressure causes the stripping of gas in galaxies, and sometimes star-forming tails and blobs can be associated with the stripped gas around gas-rich disk galaxies (e.g., Fumagalli et al. 2014; Kenney et al. 2014). Late-type galaxies that present these characteristic features are often referred to as "jellyfish" galaxies.

Such a jellyfish-like feature has not yet been reported in elliptical galaxies, probably due to their gas-poor nature. However, elliptical galaxies are also subject to ram pressure when they enter into the ICM. Deep X-ray observations have shown peculiar structures of hot gas halos stripped from some elliptical galaxies, for instance, NGC 4406 (Forman et al. 1979; White et al. 1991), NGC 4472 (Irwin & Sarazin 1996), and NGC 4552 (Machacek et al. 2006) in the Virgo cluster and NGC 1404 (Machacek et al. 2005) in the Fornax cluster. Although those elliptical galaxies are going through the same mechanism as the star-forming jellyfish galaxies, it is unlikely to substantially affect the evolution of the elliptical galaxies due to their low levels of star formation (Kenney & Koopmann 1999).

In this Letter, we report an elliptical galaxy that suffers from ram-pressure stripping with star-forming blobs and ionized gas tails in Abell 2670 ($z = 0.076$). The galaxy was discovered using deep optical images taken in order to search for post-merger signatures from red sequence galaxies in galaxy clusters (Sheen et al. 2012, 2016). In the deep images the galaxy shows disturbed halo features and is surrounded by several blue blobs, which is unusual for an elliptical galaxy (Figure 1). In order to confirm the association of the blue blobs with the galaxy, we first conducted IFU (Integral Field Unit) spectroscopic observations of this galaxy using MUSE (Multi Unit Spectroscopic Explorer) on VLT (Very Large Telescope). The MUSE data revealed an unexpected complex hidden structure of gas within and surrounding the galaxy, which indicates that the galaxy is experiencing strong ram-pressure stripping in the cluster environment.

2. Data

We obtained MUSE IFU spectra of the galaxy as a part of ESO program 094.B-0921(A) (PI Yun-Kyeong Sheen). Taking advantage of the revolutionarily wide field of view ($1' \times 1'$) of MUSE, it was possible to simultaneously observe the galaxy at $z = 0.08$ and nearby star-forming blobs. In order to include luminous blue blobs at the north of the galaxy, we took two MUSE fields of view as shown in Figure 1. The total exposure time is 1 hr (4×900 s) and half an hour (6×300 s) for the fields (A) and (B), respectively. The MUSE spectral range is 4650–9300 Å and the spatial resolution is $0\farcs2$ in Wide Field Mode. The data were reduced using MUSE pipeline version 1.6 with EsoRex (ESO Recipe Execution Tool) version 3.12.3. The object frames were stacked to a final data cube for each field.

3. Ram-pressure Stripping of an Elliptical Galaxy

3.1. Discovery of a Gas Disk, Long Ionized Gas Tails, and Star-forming Blobs

We performed spectral fitting of the final data cubes using the IDL software KUBEVIZ (Fossati et al. 2015). A spectrum

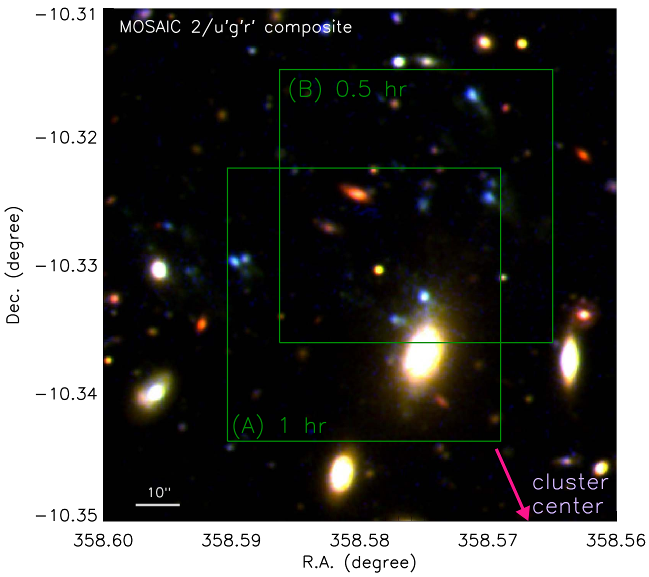

Figure 1. MUSE fields of view ($1' \times 1'$ for each square) are superimposed on a pseudo-color image of the galaxy. The composite image was made of u', g', r' deep images taken with Blanco/MOSAIC 2. (A) and (B) fields were taken with MUSE for 1 hr and 0.5 hr, respectively. Blue blobs were discovered in the opposite direction from cluster center. Also, the deep images revealed stellar tails of those blue blobs.

from each spaxel was fitted using Hα emission lines, as well as continuum spectra, to derive the Hα flux and line of sight velocities with respect to the velocity of the galaxy center ($z_{\rm SDSS} = 0.08$). The entire Hα flux map from fields (A) and (B) is presented in Figure 2(a). The MUSE data reveals the presence of an extended Hα disk at the galaxy center, with bright concentrated emission at the center, and astonishingly long ionized gas tails emanating from the disk. The tails are visible out to more than 80 kpc from the galaxy. The data also shows Hα blobs located at the positions corresponding to the blue blobs found in our deep optical images (see Figure 1).

Figure 2(b) presents a velocity map of the ionized gas using the Hα emission line. There is a clear indication of rotation in the gas disk of the galaxy, and this velocity field extends into the dynamics of the ionized gas tails. The star-forming blobs also seem to well match the velocity field of the rotating gas disk and stripped gas. This behavior was also reported in ESO137-001 (Fumagalli et al. 2014), a spiral galaxy experiencing extreme ram-pressure stripping, but this is the first time, to the authors' knowledge, that similar behavior has been reported for an elliptical galaxy.

3.2. Is It Really an Elliptical Galaxy?

The origin of the gas detected in the galaxy is uncertain. From the color and morphology, it might be assumed that the galaxy was early-type. If so, then the most simple and plausible scenario is that the gas was brought into the galaxy by a recent wet merger with a gas-rich companion galaxy. The disturbed stellar halo of the galaxy, revealed in the deep optical images, supports this scenario as it shows classical post-merger morphological features. However, it is not impossible that the main galaxy might, in fact, have been a late-type galaxy, and so the gas was not brought in externally. To try to understand which scenario is more likely, we studied the morphology and stellar dynamics of the galaxy in more detail.

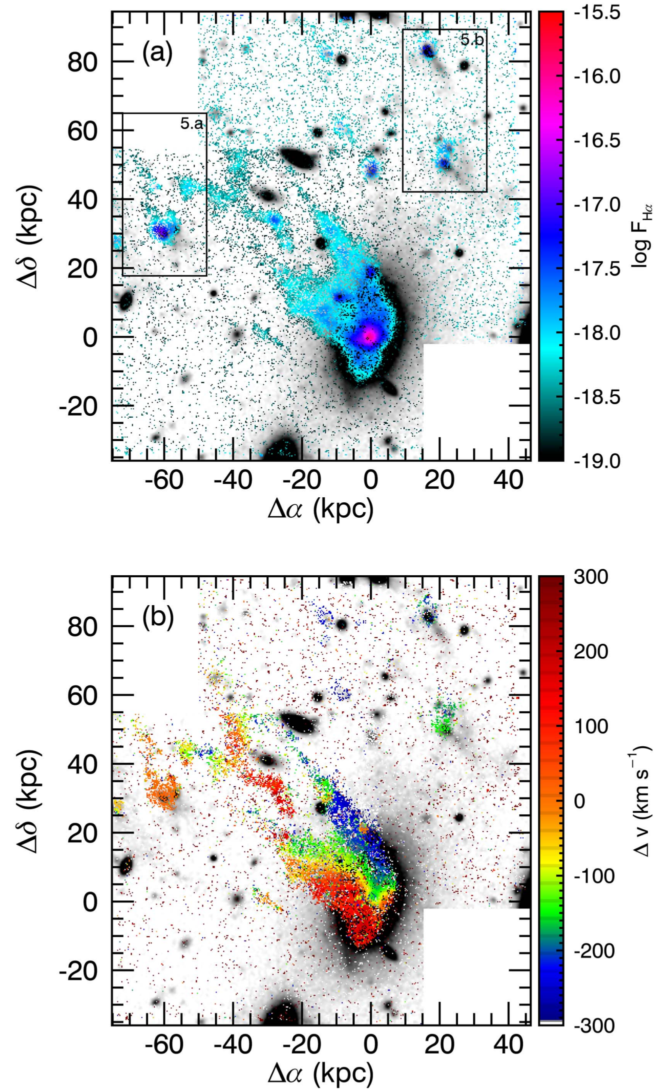

Figure 2. (a) Hα flux map and (b) velocity offset map from the Hα of the whole field of view. The zoom-in areas for blue blobs of Figure 5 are indicated with boxes (5(a) and (b)) in the Hα map.

To investigate its morphology, we performed unsharp masking of the galaxy. We used an ellipse model, derived by the `ellipse` task of `IRAF`. Figure 3 shows (a) a r'-band image of the galaxy, (b) a model image, and (c) a residual image after the model was subtracted from the r'-band image. As shown in Figure 3(c), we do not see any hint of a stellar disk in the residual image. We fitted its radial surface brightness profile using a combined model of a Sérsic profile and an exponential profile, in order to derive a bulge-to-total (B/T) ratio and the best-matching Sérsic index of the galaxy (Figure 3(d)). As a result, we found that the B/T ratio $\approx$1 and the best-matching Sérsic index from the combined model is greater than 4 ($n = 5.86$). This result demonstrates that the galaxy is an elliptical galaxy with no evidence of a stellar disk.

We also examined the stellar kinematics of the galaxy using the MUSE data. In the spectra of the galaxy's central region, the stellar absorption lines are as prominent as the gas emission lines. They indicate that the stellar component consists primarily of old stellar populations, while the Hα emitting gas disk suggests ongoing star formation. We utilized an IDL program, Penalized Pixel-Fitting (pPXF; Cappellari & Emsellem 2004;

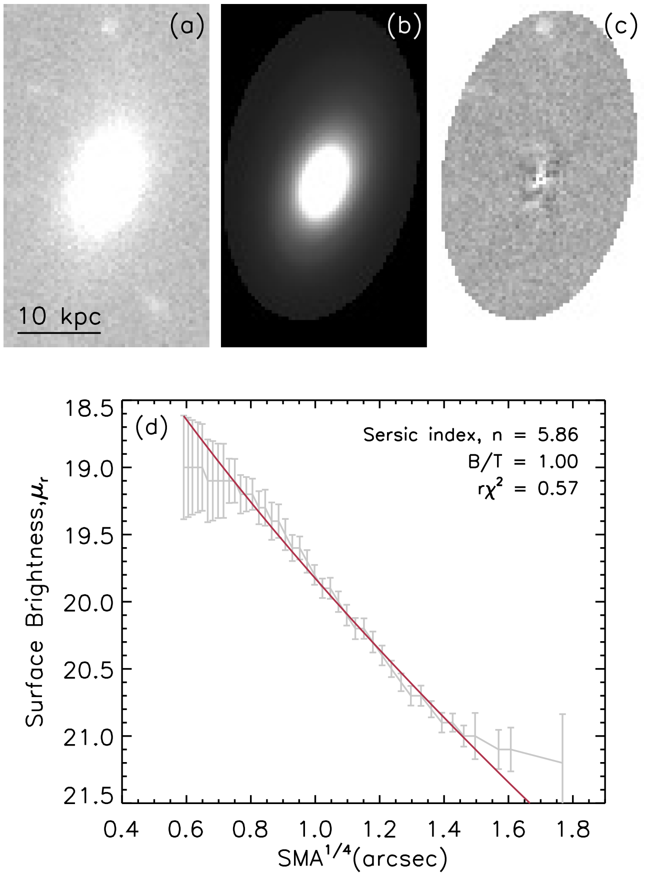

Figure 3. (a) MOSAIC 2 r'-band snapshot image ($t_{\rm exp} = 60$ s), (b) `ellipse` model of the galaxy, (c) a residual image after the model is subtracted from the image. The radial surface brightness profile is fitted using a combined model of a Sérsic profile and an exponential profile. The result is presented in (d). The profile and errors from the data points are presented in gray and the best fit is shown by a red line. Although we applied a combined model, the result suggests that an exponential profile is negligible for this galaxy as B/T = 1. The best Sérsic index, n, of the profile also turned out to be greater than 4 ($n = 5.86$) using the combined model.

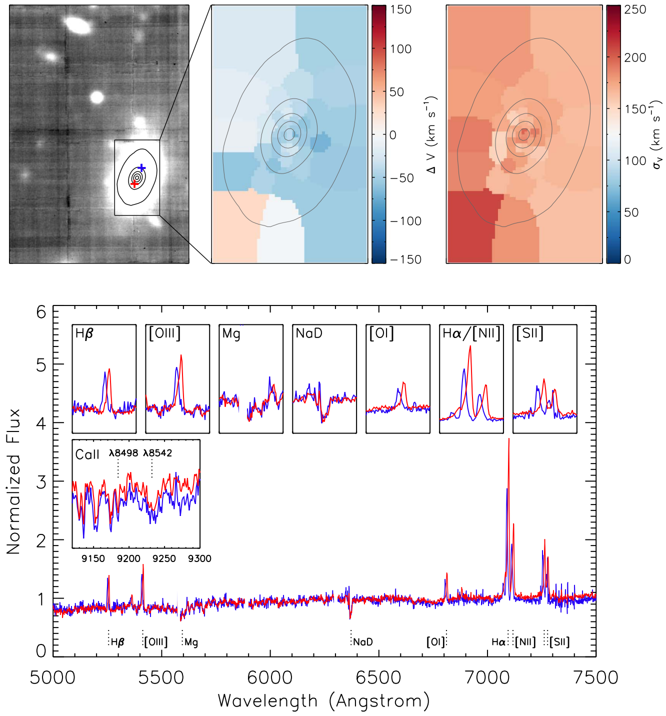

Figure 4. Top, from left to right panels: MUSE white-light image, stellar velocity, and velocity dispersion maps derived by pPXF. Contours are drawn for different flux levels around the galaxy center: 10, 50, 100, 150, and 200 $\times$ 10^{-20} erg s^{-1} cm^{-2} Å^{-1}, from the MUSE white-light image. Bottom: MUSE spectra are presented to show the wavelength shifts of prominent emission lines along the plane of a gas disk, while absorption lines (Mg, NaD, and Ca II λ8498, λ8542) remain at the same wavelength in the two spectra. The blue and red spectra correspond to the regions of blue and red crosses in the white-light image, respectively. The inset images extend for 90 Å centered on the line features, except the two Ca II triplet lines. The sky residuals are erased in the spectra.

Cappellari 2016), to derive stellar kinematics using absorption lines. The program fitted MUSE spectra with the MILES Library of Stellar Spectra (Sánchez-Blázquez et al. 2006), covering a spectral range of 3525–7500 Å. Since MUSE spectra start from 4750A, the valid wavelength range for the pPXF was 4750–8100 Å (4400–7500 Å in the rest frame). Before running the pPXF, the Voronoi 2D-binning method (Cappellari & Copin 2003) was applied to the final data cube to achieve S/N = 30 at 5500 Å in each bin. The velocity offset of stars with respect to the galaxy ($z = 0.08$), and the velocity dispersion in each bin, are presented in Figure 4. Interestingly, we find that there is no hint of rotation in the stars. The galaxy is a dispersion-supported system, with a high velocity dispersion, as shown in Figure 4. MUSE spectra are presented in the figure to show the wavelength shifts of prominent emission lines along the plane of a gas disk, while absorption lines remain at the same wavelength. Two Ca II triplet lines are included in the figure to support that there is no significant rotation of stars, although they were not utilized for the calculation of stellar velocity offsets.

Based on its surface brightness profile, elliptical shape, and the total lack of rotation seen in the stellar kinematics, we believe that it is an elliptical galaxy. These results are discussed further in Section 4.

3.3. Morphology of Star-forming Blobs

In Figure 5, we zoom in on some of the star-forming blobs. The Hα map is superimposed over the deep r'-band image. We find that the blobs often have a tadpole-like morphology. The head of the blobs emits strong Hα. The blobs also have a white tail, visible only in the optical. These are stellar tails, and they tend to point toward the cluster center. Previously, objects such as these have been explained using the "Fireball model" of Kenney et al. (2014). This suggests that the star-forming blobs are experiencing a ram pressure that accelerates them, leaving the stellar components behind. For this reason, the stellar tails are expected to point in the opposite direction to where the blobs are being accelerated (refer to Figure 16 in Kenney et al. 2014). In that paper, the model is proposed to explain the elongated NUV distribution around the "fireballs" of the dwarf irregular galaxy IC 3418 in the Virgo cluster. However, thanks to our deep imaging, here the stellar tails are revealed clearly in the optical. We also note the presence of streams of ionized gas, in the opposite direction to the stellar streams. This is expected if the ram pressure, which accelerates the star-forming blobs, also strips a little ionized gas from the blobs themselves. Thus, under the actions of ram pressure, there is a clear segregation, with streams of ionized gas blowing downwind from the blob and streams of stars pointing upwind. A schematic view of the star-forming blobs is shown in Figure 5(c). Similar behavior is also expected when tidal

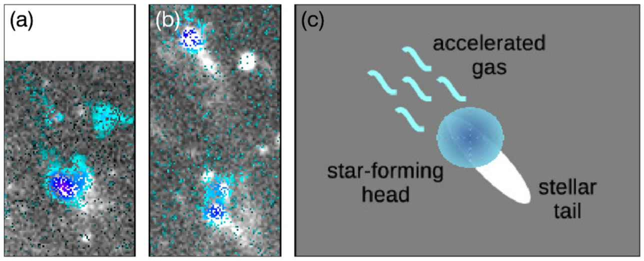

Figure 5. (a) and (b) Zoom-in images of some of the star-forming blobs, with the Hα flux map superimposed over the deep r'-band image, (c) schematic view of the blobs.

dwarf galaxies (TDGs) undergo ram-pressure stripping (e.g., see Figure 1 of Smith et al. 2013).

4. Discussion

We report the discovery of an elliptical galaxy with one-sided, long ionized gas tails. The tails point away from the cluster center, which suggests that the galaxy is currently experiencing ram-pressure stripping in Abell 2670. Simulations of ram-pressure stripping have shown that it is easier to strip the more weakly bound ionized hot gas from a galaxy than the less-extended cooler disk gas (Bekki 2009). In addition, there are several blue star-forming blobs, with a tadpole-like morphology, surrounding the galaxy. Their stellar tails point upstream, toward the cluster center, further supporting the theory that the ionized tail and star-forming blobs are actively undergoing ram-pressure stripping.

Based on morphology and optical colors, the main galaxy would be classified as early-type. The residual image between the galaxy and its ellipse model does not show any hint of stellar disk. Moreover, the velocity field of the galaxy, measured using the stellar absorption lines, shows no indication of significant rotation. Indeed, the velocity dispersions are as large as $\sim$200 km s^{-1} in the galaxy center. Thus, the stellar kinematics strongly suggest that the galaxy is, in fact, an elliptical galaxy, with emanating streams of ionized gas.

Where does the gas come from? A likely scenario is that a wet merger occurred. Many merger features are apparent, as indicated by disturbed halo features and stellar streams in our deep optical imaging.

The true origin of the star-forming blobs is uncertain. In other jellyfish systems, often the star-forming blobs external to the galaxy are found in a narrow strip, directly downwind of a galaxy that is undergoing ram-pressure stripping. This gives the impression that the blobs are forming from the ram-pressure-stripped gas itself (e.g., see Figure 1 of Kenney et al. 2014). However, in our case, the star-forming blobs are spread over a wide range of angles, beyond the galaxy and its ionized gas tails. Therefore, for the blobs to have formed from ram-pressure-stripped gas, the ram-pressure wind would have needed to change direction significantly. Moreover, the stellar mass range of our star-forming blobs, based on their $g' - r'$ colors (Bell et al. 2003), is comparable to that of dwarf galaxies ($\log(M_{\star,\mathrm{blob}}/M_{\odot}) = 7.6$–$8.4$). Therefore, another possibility is that these star-forming blobs are, in fact, TDGs formed during the wet merger. This could explain their large masses and lack of a spatial correlation with the ionized gas stream.

Regardless of whether they formed from ram-pressure-stripped gas or are TDGs, their tadpole-like morphology suggests they are actively experiencing ram pressure now. Smith et al. (2013) demonstrated that ram pressure acting on TDGs produces stellar streams that point upwind, in the same way as seen in the "fireball model" (Kenney et al. 2014). This is because, in both scenarios, a star-forming blob of gas is accelerated by ram pressure and leaves behind a trail of stars, and this occurs independently of how the star-forming blob was originally formed.

From the H$_\alpha$ emission map, star formation in the center of the galaxy appears very centrally concentrated. This, too, is fully consistent with the merger scenario, where gas can be driven to a galaxy's center by tidal torques and dissipation, resulting in central starbursts (Ellison et al. 2013; Moreno et al. 2015). The fact that the main galaxy also shows a very red optical color ($g' - r' = 0.99$) implies there must be very heavy internal extinction, which reddens the light from the young and blue stellar populations recently formed at its center. We note that the formation of young stars within the gas disk could result in a small, rotating stellar disk in the center. Such an object would resemble kinematically decoupled cores in early-type galaxies (Emsellem et al. 2007; i.e., in this case, with a rotating young component surrounded by a non-rotating older component). However, so far we do not detect any evidence for such a stellar disk. This might suggest that the gas has not been star-forming for very long. Given the very red optical color of the main galaxy, however, we cannot rule out the possibility that strong dust extinction is obscuring our view of such a disk (Stickley & Canalizo 2016).

To draw stronger conclusions, additional investigation is needed to measure the amount of gas in the system, and to get the actual star formation rate. However, this is beyond the scope of this discovery paper. We will attempt to answer this, and the many other open questions that were raised in this study (e.g., the properties of stellar populations in different star-forming regions of the system), in a follow-up paper.

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Facilities: VLT:Yepun (MUSE), Blanco (MOSAIC 2 CCD Imager).

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