DISCOVERY OF A POSSIBLY SINGLE BLUE SUPERGIANT STAR IN THE INTRA-CLUSTER REGION OF VIRGO CLUSTER OF GALAXIES

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ABSTRACT

IC 3418 is a dwarf irregular galaxy falling into the Virgo cluster, and a 17 kpc long trail is seen behind the galaxy, which is considered to have formed due to ram pressure stripping. The trail contains compact knots and diffuse blobs of ultraviolet and blue optical emission and, thus, it is a clear site of recent star formation but in an unusual environment, surrounded by a million degree intra-cluster medium. We report on our optical spectroscopy of a compact source in the trail, SDSS J122952.66+112227.8, and show that the optical spectrum is dominated by emission from a massive blue supergiant star. If confirmed, our report would mark the farthest star with spectroscopic observation. We interpret that a massive O-type star formed in situ in the trail has evolved recently out of the main sequence into this blue supergiant phase, and now lacks any detectable spectral sign of its associated 

Key words: galaxies: clusters: individual (Virgo) – galaxies: individual (IC 3418) – intergalactic medium – supergiants – stars: formation

Online-only material: color figures

1. INTRODUCTION

As galaxies fall into the huge gravitational potential of clusters of galaxies with high velocity, interaction with the hot intra-cluster medium strips off cool gas from the main body of the infalling galaxies into the intra-cluster region (Gunn & Gott 1972; Vollmer et al. 2001). Studying the fate of this stripped gas, ionization in contact with a million degree intra-cluster medium, or condensation to form new stars, is of great interest. The Virgo cluster is the closest massive cluster of galaxies (16.5 Mpc; Mei et al. 2007) and is an ideal laboratory to investigate details of such processes. We focus on IC 3418, a galaxy likely falling into the Virgo cluster for the first time at a very high speed (nearly 1000 km s⁻¹; Vollmer et al. 2001), especially on its 17 kpc long trail which is considered to have formed behind the galaxy due to ram pressure stripping (Hester et al. 2010; Fumagalli et al. 2011). The trail is manifested as a chain of blobs seen in both GALEX (Martin et al. 2005) UV continuum and Hα emission-line images (Hester et al. 2010; Fumagalli et al. 2011). Both of these emissions are clear signs of recent star formation, and therefore the trail is the best target to explore details of a young massive stellar population in the intra-cluster region. Stellar spectroscopy is unique and useful not only because it provides basic stellar properties (e.g., age, metallicity, luminosity), but also because we can explore a potentially new mode of star formation in this special condition. We expect that such star formation is quite different from those in the Milky Way, and such a study will eventually contribute to the understanding of galaxy evolution under cluster environment (Gunn & Gott 1972) and intra-cluster stellar population.

In this Letter, we report on our spectroscopic studies of SDSS J122952.66+112227.8 (hereafter SDSS J1229+1122), a compact source of optical emission within the star-forming trail of IC 3418.

2. SPECTROSCOPIC OBSERVATION AND PHOTOMETRY ON ARCHIVAL IMAGES

The FOCAS spectrograph at the Subaru telescope (Kashikawa et al. 2002) was used on the night of 2011 April 27 in multi-slit spectroscopy mode to study the nature of the trail of IC 3418. One of our slitlets was put on a faint (g_AB = 23.0 mag) blue compact object catalogued earlier as SDSS J1229+1122 and located near the far end of the trail (Figures 1 and 2). Low-resolution spectrum was taken with an 0.8 wide slit and a “300B” grism for spectral resolution R(≡ λ/δλ) of ~7000 to cover 4000–7000 Å, and the total exposure time was 6000 s. Galactic extinction for E(B – V) = 0.03 mag was corrected based on the NASA Extragalactic Database (NED) information. The absolute flux scale of the spectrum was re-calibrated based on our photometric data (see below), and a small slit-loss correction (by 7%) was applied. Additionally, a shorter exposure (3600 s) but with relatively higher (“medium”) spectral resolution (R ~ 3750) spectrum was obtained with the same slit width and “VPH680” grism, resulting in a FWHM velocity resolution of ~80 km s⁻¹. Low-resolution spectrum is shown in Figure 3, and measured spectroscopic properties on both spectra are summarized in Table 1.

We also performed photometric analysis on archival images to supplement our spectroscopy (Figures 1 and 2). Canada–France–Hawaii Telescope (CFHT) Megacam (Boulade et al. 2003) images were taken from Megapipe (Gwyn 2008) at the g, i', z' bands, and another image at the u* band was locally stacked based on individually pre-calibrated archival images available at the CFHT Science Data Archive. All those images were originally taken for the New Generation Virgo cluster Survey (NGVCS) project (Ferrarese et al. 2012). SDSS J1229+1122 has a faint nearby source within 1″ from our spectroscopic target source, which was not resolved in the Sloan
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3. RESULTS

The low-resolution spectrum of SDSS J1229+1122 can be characterized by strong Hα (at equivalent width (EW) of $-34$ Å) and weak Hβ emission lines on blue continuum. The Hα line is slightly resolved with our medium-resolution spectrum, having a FWHM of $\sim 164$ km s$^{-1}$ (corrected for the instrumental resolution), but further line profile analysis was not possible. Our spectroscopic Hα flux ($5.0 \times 10^{-17}$ erg s$^{-1}$ cm$^{-2}$) is below the detection limit of our Hα image (Figure 2). The Hα flux is $\lesssim 10$ times fainter than nearby compact Hα emitters within the trail (Hester et al. 2010; Fumagalli et al. 2011; see also Figure 2). Our medium-resolution spectrum shows that the heliocentric velocity is $-99$ km s$^{-1}$, which is very close to that of IC 3418 ($38$ km s$^{-1}$; Gavazzi et al. 2004). Their similar recession velocities as well as spatial association of SDSS J1229+1122 with the trail of IC 3418 (Figure 1) strongly indicate that they are physically associated to each other within the Virgo cluster.

At a distance of 16.5 Mpc (or $m-M = 31.1$; Mei et al. 2007), the absolute magnitude ($M_V$) is $\sim -8.3$ and the Hα luminosity is $1.6 \times 10^{36}$ erg s$^{-1}$. The H$\alpha$ luminosity is about 5–100 times fainter than in known intra-cluster H II regions around NGC 4388 (Gerhard et al. 2002; Cortese et al. 2004) and about 10 times fainter than those around the VCC 1249/M 49.
merging system (Arrigoni Battaia et al. 2012) in the Virgo cluster. In one of these known H\textsc{ii} regions, where detailed spectroscopic analyses were made, only a few O-type stars were estimated to be powerful enough for the observed luminosity (Gerhard et al. 2002).

We find that the emission-line ratios of SDSS J1229+1122 are unusual for photo- or shock-ionized nebulae. Other than H\textalpha{} and H\beta{}, no nebular forbidden lines were detected, including ones that are typically bright in those nebulae ([O\textsc{iii}] \lambda{}5007 Å, [N\textsc{ii}] \lambda\lambda{}6548,6583 Å, and [S\textsc{ii}] \lambda\lambda{}6717,6731 Å; Figure 3). Their upper limits were measured assuming the same line widths and redshift as Balmer emission lines (Table 1). Stringent upper limits on low ionization [N\textsc{ii}] and [S\textsc{ii}] and undetected higher ionization [O\textsc{iii}] lines strongly indicate that the emission originates from neither H\textsc{ii} regions nor shock-ionized nebulae (Veilleux & Osterbrock 1987) but from hot stellar atmosphere. We also note that other emission lines seen typically in luminous blue variable (LBV) stars besides Balmer lines, such as [He\textsc{i}] \lambda{}5878 Å and [Fe\textsc{ii}] \lambda{}5018 Å, were not detected.

Such a luminous compact object with blue continuum should either be a young stellar association or a single blue (super)giant star. We first searched a stellar spectrum library (Pickles 1998) for matching the continuum (below H\alpha{} and excluding H\beta{} emission lines) and the broadband photometric data, and found that A2 supergiant (I) is the best match to the observation (Figure 4). A similar blue continuum can be reproduced by the A5 dwarf (V), but its u* flux is expected to be fainter than the observation and its intrinsically faint luminosity does not agree with the observation (Figure 4). Then we searched starburst99 models of instantaneous star formation (Leitherer et al. 1999) for the same purpose. Continuous star formation models are not considered since they should always show H\textsc{ii}-region-like spectrum, unlike our observation. We chose a model of 0.4 solar metallicity (Z = 0.008) based on metallicity measurements with other intra-cluster H\textsc{ii} regions in the Virgo cluster (Gerhard et al. 2002; Arrigoni Battaia et al. 2012). The shape of the initial mass function (IMF) cannot be examined, and we only describe here cases with IMF slope (\alpha{}) = 2.35 and M_{upper} = 100 M_{\odot} since the basic results hold with other IMF parameter sets. Although the model grid provided by Leitherer et al. (1999) is not fine enough to find statistically satisfactory models for all photometry data, we found three possible burst ages to match the observation: 6 Myr, 16 Myr, and 20 Myr (Figure 4). We found three solutions because, in addition to main-sequence stars that become monotonically redder with age, enhanced red supergiant contribution quickly makes the color redder around \sim{}10 Myr (or between 6 and 16 Myr in the assumed model parameters) when most O-type stars evolve away from the main sequence. Note that the very similar trend of color change is seen for all different IMF parameter sets. In summary, both possibilities of a blue supergiant (hereafter BSG) star and young (6–20 Myr) stellar association are equally good to reproduce the observed blue continuum spectrum and broadband photometry.

Figure 3. Top panel: low-resolution optical spectrum and u*, g*, and i*-band photometry (blue with error bars) of SDSS J1229+1122. 1\sigma{} noise spectrum is shown near the bottom of all plots. Bottom left: the same spectrum as the top panel but around H\beta{} and [O\textsc{iii}]. Multi-Gaussian fitting (plus linear function for the continuum) results and the line wavelengths are overlaid with cyan dashed lines. Neither [O\textsc{iii}] \lambda{}4959 nor \lambda{}5007 is detected but their expected wavelengths for the redshift of H\beta{} are marked. Bottom right: the same spectrum as the top panel but around H\alpha{}, [N\textsc{ii}], and [S\textsc{ii}]. Multi-Gaussian fitting results are shown in the same way as for the bottom left. Neither [N\textsc{ii}] \lambda{}6583, [S\textsc{ii}] \lambda\lambda{}6717,6731 Å is detected but their expected wavelengths for the redshift of H\alpha{} are marked.

(A color version of this figure is available in the online journal.)
Figure 4. Comparison of the observed low-resolution spectrum and photometry data for the $u^*$, $g'$, $i'$, and $z'$ bands (blue with error bars) of SDSS J1229+1122 (top) with model spectra. Model spectra are scaled at the $g'$ band to the observation, and then offset by $-0.25$ in log flux scale along with the photometry data for clarity of the figure. As labeled, the second, third, and fourth spectra are starburst99 instantaneous models of 6 Myr, 16 Myr, and 20 Myr, and the following two spectra are of A2 I and A5 V stars, respectively. The expected $u^*$ fluxes for each model are marked with red crosses.

(A color version of this figure is available in the online journal.)

Table 1
Photometric and Spectroscopic Characteristics of SDSS J1229+1122

|               | R.A. (2000) | Dec. (2000) |
|---------------|------------|-------------|
| Megacam Astrometry | 12h29m52s69 | +11°22′28.0″ |
| Megacam photometry* | Observed | Correctedb |
| $u^*$         | 23.29 ± 0.02 | 23.15 ± 0.02 |
| $g'$         | 22.96 ± 0.01 | 22.85 ± 0.01 |
| $i'$         | 23.09 ± 0.02 | 23.03 ± 0.02 |
| $z'$         | 23.16 ± 0.04 | 23.12 ± 0.04 |
| Bessel photometryb,c | Apparent | Absoluted |
| $V$          | 22.85 ± 0.01 | $M_V = -8.25$ |

FOCAS low-resolution spectroscopy

| Emission-line ratios | 3σ upper limit |
|---------------------|----------------|
| [OIII] $λ$5007/Hβ   | <0.28           |
| [NII] $λ$6583/Hα    | <0.028          |
| [SII] $λ$6717+6731/Hα | <0.031         |

FOCAS medium-resolution spectroscopy

| $H\alpha$ heliocentric velocity | $-99 \pm 6$ km s$^{-1}$ |
| $H\alpha$ intrinsic line width | $164 \pm 22$ km s$^{-1}$ FWHM |

Notes.

a In Megacam SDSS (AB) system.
b Galactic extinction corrected for $E(B - V) = 0.03$.
c Bessel system in Vega unit, converted based on our spectrum.
d Distance modulus of $m - M = 31.1$ is used.

4. DISCUSSIONS

4.1. SDSS J1229+1122: A Compact Young Stellar Association or a Single Blue Supergiant Star?

In the model of instantaneous starburst, the emission-line component of SDSS J1229+1122 should originate from ionized by young massive stars within the stellar association. Since EW(Hα) monotonically decreases with burst age, only the $\sim 6$ Myr model among the three possibilities can reproduce rather large observed EW(Hα) ($\sim 34$ Å) due to the remaining main-sequence O-type stars (Leitherer et al. 1999). The continuum luminosity then requires a stellar mass of $\sim 10^4 M_\odot$, and the expected number of O-type stars there is several—several tens depending on the choices of the IMF parameters—producing a luminous H II region spectrum that is not observed. The next possibility is that a stellar association of $\sim 16$–20 Myr dominates the observed continuum and extra $H\alpha$ emitting source(s) in addition to the regular population producing strong $H\alpha$. Possible extra emission-line components are classical Be stars (Lamers et al. 1998; Paul et al. 2012), supergiant Be stars, and supergiant A stars (Tully & Wolff 1984; McCarthy et al. 1997). All of them show prominent $H\alpha$ emission without nebular lines, and their EW($H\alpha$) alone is already comparable to the observed one (e.g., Tully & Wolff 1984; Paul et al. 2012), indicating that those stars dominate the observed spectrum since underlying spectrum from regular stellar association, if any, will dilute the observed width. The observed absolute magnitude ($M_V \sim -8.3$) requires either a single BSG or 50–200 classical Be stars (class III–V; Lamers et al. 1998; Paul et al. 2012), since they are fainter by 4–6 mag than BSGs. If SDSS J1229+1122 is made entirely of classical Be stars, such a large number of short-lived objects within a compact ($\leq 60$ pc across) stellar association requires a very unlikely star formation episode. Instead, if it is a BSG, both
the absolute magnitude and EW(Hα) are within the range of AO1 stars in the Small Magellanic Cloud (Tully & Wolff 1984), although the observed EW(Hβ) is larger by a factor of ~2. Since the EW in BSGs is a function of metallicity, luminosity, and stellar type (Tully & Wolff 1984), we believe that our observation is within the probable range of BSGs given the uncertainties of detailed stellar parameters for SDSS J1229+1122. Observed intrinsically broad (FWHM of ~164 km s⁻¹) Hα emission hints at the presence of a strong stellar wind and/or a fast rotating equatorial disk, although their characteristic profile (e.g., P-Cyg type for BSGs; McCarthy et al. 1997; Prybilla et al. 2006) could not be discerned. Therefore, a model of a single BSG as the optically dominant sources within SDSS J1229+1122 is strongly preferred over a model of young stellar association. Note, however, that we cannot distinguish between the case of a single star or a collection of a few such stars based on our observation, although only a single such star is bright enough. We expect that SDSS J1229+1122 was an H II region about a few to several Myr ago and similar in nature to other known H II regions in the trail of IC 3418 (Hester et al. 2010; Fumagalli et al. 2011) and those within the Virgo cluster (Gerhard et al. 2002; Cortese et al. 2004; Arrigoni Battaia et al. 2012).

4.2. Star Formation Characteristics within the Cluster Environment

Stars usually form in dusty giant molecular gas clouds, but such clouds are too tightly bound with the galaxy to be stripped off by ram pressure stripping and thrown into the gaseous trail of cluster-infalling galaxies (Hester et al. 2010). However, a few rare trails including that of IC 3418 and others that extend up to 90 kpc from the parent galaxy are seen decorated with UV-bright, Hα emitting, and/or optically blue young star-forming clumps (Cortese et al. 2007; Yoshida et al. 2008; Hester et al. 2010; Fumagalli et al. 2011; Arrigoni Battaia et al. 2012). Fumagalli et al. (2011) analyzed the stellar properties of IC 3418 based on optical and GALEX-UV spectral energy distribution (SED), and argue that the star formation there was truncated about 200 Myr ago due to ram pressure stripping. As massive stars are short-lived, the O-type star, which has evolved into a BSG by now, must have formed a few 10 Myr ago within SDSS J1229+1122, i.e., after the truncation of star formation within IC 3418. This supports the idea that the star has formed in situ within the trail.

SDSS J1229+1122 is located within a diffuse GALEX NUV blob, labeled “D3” by Hester et al. (2010), or a “lower surface brightness and visually diffuse filament,” labeled “F1” by Fumagalli et al. (2011). The blob extends ~10′ or ~800 pc. Fumagalli et al. (2011) reported a 2.3 mag brighter g’-band magnitude for F1 than our measurement on SDSS J1229+1122, and analyzed that the overall SED, including GALEX-UV bands, can be reproduced by a young stellar population with an age of 640 ± 144 Myr and a mass of 3.48 ± 0.05 M⊙. However, the CFHT image shows only a few more faint compact sources besides SDSS J1229+1122 there (Figure 2), indicating that there is an unresolved diffuse young stellar population within the blob. We speculate that there are many more unexplored populations of blue stellar populations within the intra-cluster region, not only along the trail of IC 3418, but also in other similar trails in the Virgo cluster.

It is likely that star formation in such a special environment is quite different from typical cases in, e.g., our own Milky Way. The difference in temperature and relative velocity between the star-forming molecular clouds and the ambient medium may be millions of degrees and ~1000 km s⁻¹, respectively. Located far from the parent galaxy, especially at the far end of the trail, the role of turbulence may be dominant over gravity. Turbulence in the trail may cause eddies to form, thus creating dense cloud clumps which would cool very fast and subsequently collapse under their own gravity to form stars. Although the model of turbulence-driven star formation seems promising (Hester et al. 2010; Fumagalli et al. 2011), constraining the detailed physical mechanism of star formation and characterizing the turbulence require further investigations of stellar populations and cool molecular gas there.

5. IMPLICATION FOR FUTURE EXTRAGALACTIC STELLAR ASTROPHYSICAL STUDIES

Various kinds of intra-cluster stellar populations have been known in the Virgo cluster: in addition to diffuse intra-cluster optical continuum light (Mihos et al. 2005), individual sources like intra-cluster H II regions (Gerhard et al. 2002; Cortese et al. 2004; Arrigoni Battaia et al. 2012), old (>10 Gyr) intra-cluster stars (Williams et al. 2007), and intra-cluster planetary nebulae (Feldmeier & Ciadullo 2004; Aguerri et al. 2005) are known. Our study, independent of the interpretation that SDSS J1229+1122 contains a single or a few more stars, has concluded that BSG reside in the intra-cluster region. Previously, BSG candidates have been photometrically identified in M 100 (Hill et al. 1998) in the Virgo cluster, and spectroscopically identified in NGC 3621 at a distance of 6.7 Mpc (Bresolin et al. 2001). Located in the Virgo cluster, and if confirmed by future observations to be a single star, SDSS J1229+1122 will be the most distant star discovered from spectroscopic observations. We demonstrated for the first time that stellar spectroscopy up to the distance of the Virgo cluster is indeed feasible as anticipated nearly two decades ago (Kudritzki et al. 1995; McCarthy et al. 1997; Bresolin et al. 2001; Kudritzki 2010). However, to reveal its true nature by detailed quantitative spectroscopic analyses, spectra with higher signal-to-noise ratios and higher resolution below Hβ (~4800 Å) as well as Hα are required. To exploit its full potential for accurate distance measurements and star formation studies in the Virgo cluster and beyond, we require next-generation giant telescopes such as Thirty Meter Telescope (TMT) and/or European Extremely Large Telescope (E-ELT; Kudritzki 2010).

Based in part on data collected at Subaru Telescope, which is operated by the National Astronomical Observatory of Japan. Based on observations obtained with MegaPrime/MegaCam, a joint project of CFHT and CEA/DAPNIA, at the Canada–France–Hawaii Telescope (CFHT), which is operated by the National Research Council (NRC) of Canada, the Institut National des Science de l’Univers of the Centre National de la Recherche Scientifique (CNRS) of France, and the University of Hawaii. This research used the facilities of the Canadian Astronomy Data Centre operated by the National Research Council of Canada with the support of the Canadian Space Agency. Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the US Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. Based on data obtained from the ESO Science Archive Facility under request number “Youichi Ohyama #35,191.” Some of the data presented in this
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