Formation of emission line dots and extremely metal-deficient dwarfs from almost dark galaxies

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ABSTRACT

Recent observations have discovered a number of extremely gas-rich very faint dwarf galaxies possibly embedded in low-mass dark matter halos. We investigate star formation histories of these gas-rich dwarf (“almost dark”) galaxies both for isolated and interacting/merging cases. We find that although star formation rates (SFRs) are very low ($<10^{-5} M_\odot \, yr^{-1}$) in the simulated dwarfs in isolation for the total halo masses ($M_h$) of $10^8 - 10^9 M_\odot$, they can be dramatically increased to be $\sim 10^{-4} M_\odot \, yr^{-1}$ when they interact or merge with other dwarfs. These interacting faint dwarfs with central compact H\,ii regions can be identified as isolated emission line dots (“ELdots”) owing to their very low surface brightness envelopes of old stars. The remnant of these interacting and merging dwarfs can finally develop central compact stellar systems with very low metallicities ($Z/Z_\odot < 0.1$), which can be identified as extremely metal-deficient (“XMD”) dwarfs. These results imply that although there would exist many faint dwarfs that can be hardly detected in the current optical observations, they can be detected as isolated ELdots or XMD dwarfs, when they interact with other galaxies and their host environments. We predict that nucleated ultra-faint dwarfs formed from the darkest dwarf merging can be identified as low-mass globular clusters owing to the very low surface brightness stellar envelopes.

Key words: galaxies: abundances – galaxies: dwarf – galaxies: evolution – galaxies: irregular – galaxies: star formation

1 INTRODUCTION

Recent spectroscopic observations have discovered apparently isolated compact H\,ii regions around galaxies (e.g., Ryan-Weber et al. 2004; Boquien et al. 2009; Werk et al. 2010, W10; Kellar et al. 2012), which are often referred to as emission line dots (“ELdots”). Clearly, some of these ELdots were observed within stripped H\,i gas of possibly interacting galaxies like NGC 1533 (Ryan-Weber et al. 2004), which suggests that such ELdots were composed purely of new stars formed from tidal debris of galaxy interaction. Indeed, previous numerical simulations demonstrated that star formation is possible in the gaseous tails stripped from gas-rich disk galaxies (Bekki et al. 2005). Some of the ELdots can be low- or high-redshifts background galaxies with the redshifted emission lines detected in the narrow filter passband adopted for observations (e.g., W10).

Although W10 confirmed that massive star formation observed as ELdots in the outer parts of disk galaxies tends to be associated with interacting galaxies, they also discovered ELdots that were located in the far outskirts of galactic disks with no signs of galaxy interaction. Such ELdots can be simply local star-forming regions of the very outer disks in gas-rich disk galaxies. It is also possible that star-forming low-mass dwarf galaxies are identified as ELdots, because their stellar envelopes are too faint to be detected in the current optical observations, they can be detected as isolated ELdots or XMD dwarfs, when they interact with other galaxies and their host environments. We predict that nucleated ultra-faint dwarfs formed from the darkest dwarf merging can be identified as low-mass globular clusters owing to the very low surface brightness stellar envelopes.

Recent observations have discovered H\,ii regions within a compact high velocity cloud and suggested that the most likely explanation for the object is a new very faint dwarf galaxy with a ratio of neutral hydrogen mass to $V$ luminosity of $M_{HI}/L_V \geq 20$ (Bellazzini et al. 2015). Stark et al. (2015) have discovered possible evidence for star formation in the Smith Cloud (Stark et al. 2015) whereas Adams et al. (2015) have discovered an isolated gas cloud (AGC198606) that would have a mass of $6.2 \times 10^5 M_\odot$ yet shows no optical counterpart. Meyer et al. (2015) have investigated the presence or absence of UV emission for HI compact cloud samples from GALFA-HI and ALFALFA blind HI surveys.
and identified 29 candidates with UV emission. They suggested that such gas-rich HI clouds with UV emission can be very low-mass dwarfs Leo P and Leo T.

It is currently unclear whether there is an evolution link between ELdots in isolated environments and extremely gas-rich, very faint dwarf (“almost dark”) galaxies such as those observed as isolated compact HVCs with or without stars. These apparently isolated clouds can be identified as ELdots, if the star formation rates (SFRs) are high enough (SFR $> 10^{-5} M_\odot$ yr$^{-1}$) to produce at least one O or B type stars (e.g., Fig. 15 in Thilker et al. 2007). It is therefore an interesting problem whether and how these extremely gas-rich dwarfs can show an observationally detectable star formation activity. Because of the lack of detailed theoretical studies of star formation in these dwarfs, it remain unclear in what physical conditions a detectable amount of star formation can be triggered in such almost dark galaxies.

The purpose of this Letter is to propose a possible evolutionary link between ELdots and extremely gas-rich low-mass dwarf galaxies based on the new results of numerical simulations of almost dark galaxies. We particularly focus on interacting and merging low-mass dwarf galaxies with their dark matter halo masses ($M_h$) equal to or less than $10^9 M_\odot$. This is because previous simulations mainly discussed the formation of blue compact dwarf galaxies (BCDs; Bekki 2008) and star formation histories (Stierwalt et al. 2015) in relatively high-mass ($M_h > 10^9 M_\odot$) interacting/merging dwarf galaxies. Although recent numerical simulations have demonstrated that dwarf-dwarf merging can cause morphological transformation of low-mass dwarf galaxies (e.g., Kazantzidis et al. 2011; Yozin & Bekki 2012), these were unable to discuss star formation histories of the galaxies. Thus, the present new simulations for $M_h \lesssim 10^9 M_\odot$ can be valuable for understanding the origin of possibly very low-mass dwarf galaxies like ultra-faint dwarfs (UFDs).

Table 1. Description of the basic parameter values for the representative low-mass dwarf models.

| Model name | $M_h (10^9 M_\odot)$ | $M_g (10^9 M_\odot)$ | $M_s (10^9 M_\odot)$ | $f_b$ | $f_g$ | $r_{vir}$ (kpc) | $c$ | $R_s$ (kpc) |
|------------|---------------------|----------------------|----------------------|-------|-------|----------------|-----|-----------|
| M1         | 1.0                 | 0.63                 | 6.3                  | $6.6 \times 10^{-3}$ | 10.0  | 7.7          | 20.0 | 0.55      |
| M2         | 1.0                 | 0.19                 | 1.9                  | $2.0 \times 10^{-3}$ | 10.0  | 7.7          | 20.0 | 0.55      |
| M3         | 1.0                 | 1.89                 | 18.9                 | $2.0 \times 10^{-2}$ | 10.0  | 7.7          | 20.0 | 0.55      |
| M4         | 1.0                 | 0.063                | 6.3                  | $6.0 \times 10^{-3}$ | 100.0 | 7.7          | 20.0 | 0.55      |
| M5         | 0.1                 | 0.063                | 6.3                  | $6.6 \times 10^{-3}$ | 10.0  | 2.5          | 25.9 | 0.18      |
| M6         | 0.1                 | 0.0063               | 6.3                  | $6.0 \times 10^{-3}$ | 100.0 | 2.5          | 25.9 | 0.18      |
| M7         | 1.0                 | 0.0                  | 0.063                | $6.0 \times 10^{-4}$ | -     | 7.7          | 20.0 | 0.55      |
| M8         | 1.0                 | 0.0                  | 0.13                 | $1.2 \times 10^{-3}$ | -     | 7.7          | 20.0 | 0.55      |

Figure 1. The distributions of gas (blue), new stars (yellow), and Hα regions (big magenta circles) at $T=0.28$ Gyr (top left) and 0.56 Gyr (top right), the time evolution of the SFR (middle), and that of the mean metallicity for new stars (bottom), in the merger model M1 with $M_h = 10^9 M_\odot$. The Hα regions are new stars that have ages less than 1 Myr and are surrounded by gas particles. For clarity, the three ELdots (Hα regions) are indicated by labels, A, B, and C. The dotted red line in the middle panel indicates the threshold SFR (SFR$_{th}$ (Hα)) above which the star-forming regions of a galaxy can be detected as Hα sources. If the SFR of a simulated dwarf at a time step is zero, then it is plotted as log$_{10}$SFR = -6.

2 THE MODEL

We investigate SFRs of low-mass dwarfs with $M_h \lesssim 10^9 M_\odot$ that are in isolation or interacting/merging with other dwarfs. In order to simulate the time evolution of SFRs and gas contents in the dwarfs, we use our original chemodynamical simulation code with dust physics that can be run on GPU machines (Bekki 2013, 2015). A dwarf galaxy is composed of dark matter halo, stellar disk, and gaseous disk in the present study. The total masses of dark matter halo, stellar disk, and gas disk are denoted as $M_h$, $M_s$, and $M_g$, respectively. The total disk mass (gas + stars) and gas mass ratio ($M_g/M_s$) are denoted as $M_g$ and $f_g$, respectively, for convenience. The baryonic mass fraction ($f_b = M_b/M_h$) in a dwarf galaxy is assumed to be a free parameter. We adopt the density distribution of the NFW halo (Navarro, Frenk & White 1996) suggested from CDM simulations and the "c-parameter" ($c = r_{vir}/r_s$, where $r_{vir}$ and $r_s$ are the virial radius of a dark matter halo and the scale length of the halo) and $r_{vir}$ are chosen appropriately for a given dark halo mass ($M_h$) by using the $c - M_h$ relation predicted by recent cosmological simulations (Neto et al. 2007).

The radial ($R$) and vertical ($Z$) density profiles of the stellar disk are assumed to be proportional to $\exp(-R/a)$ with scale length $R_0 = 2R_s$ and to $\exp(Z/Z_0)$ with scale length $Z_0 = 0.04R_s$, respectively. The gas disk with a size $R_g = 2R_s$ has the radial scale length of 0.5$R_s$ and a vertical scale lengths of 0.02$R_s$. We adopt the reasonable values for $f_g$ and $f_b$ in the dwarf models by using the observed corre-
lations between $M_{\text{HI}}$ and $M_\star$ and between $M_\text{h}$ and $M_\text{g} + M_\star$ (Papastergis et al. 2012). We mainly investigate the models with $M_\text{h} = 10^8 M_\odot$ or $10^9 M_\odot$, $f_\text{g} = 10$ or 100, and $f_\text{h}$ ranging from $6 \times 10^{-3}$ to $2 \times 10^{-2}$.

We investigate both (i) isolated models in which dwarfs do not interact with other galaxies and their host environments at all and (ii) interacting/merging models in which two equal-mass dwarfs interact or merge with each other. The initial distance and the pericenter distance ($R_p$) of two interacting/merging dwarfs are set to be $10 R_\text{s}$ and $0.5 R_\text{s}$, respectively. The orbital eccentricity ($e_p$) is set to be 1.2 (i.e., hyperbolic encounter) and 1 for the interacting and merging models, respectively. The spin of each galaxy in an interacting or merging pair is specified by angles $\theta_i$ (in units of degrees), where suffix $i$ is used to identify each galaxy. $\theta_i$ is the angle between the z axis and the vector of the angular momentum of a disk. We show the results of the models with $\theta_1 = 30$ and $\theta_2 = 45$.

A gas particle can be converted into a new star if (i) the local dynamical time scale is shorter than the sound crossing time scale (mimicking the Jeans instability), (ii) the local velocity field is identified as being consistent with gravitationally collapsing (i.e., div $v < 0$), and (iii) the local density exceeds a threshold density for star formation ($\rho_\text{th}$). We mainly investigate the models with $\rho_\text{th} = 10$ atoms cm$^{-3}$. We adopt the Kennicutt-Schmidt law ($\text{SFR} \propto \rho_\text{th}^{1.5}$, where $\rho_\text{th}$ is a gas density; Kennicutt 1998) for star formation. The models for chemical evolution and supernova (SN) feedback effects are the same as those adopted in Bekki (2013). The initial gaseous metallicity is set to be [Fe/H] = −1.6 dex in all models.

The total numbers of particles used for a merger model is $1.1 \times 10^6$, and the mass resolution for gaseous components is $1.2 \times 10^2 M_\odot$ ($1.1 \times 10^6 M_\odot$) for $M_\text{h} = 10^8 M_\odot$ ($10^9 M_\odot$). The softening length is assumed to be the same between old stellar, gaseous, and new stellar particles in the present study. The gravitational softening length for dark and baryonic components are 62 pc and 8 pc, respectively, for $M_\text{h} = 10^9 M_\odot$. These values are different in models with different $M_\text{h}$.

We mainly present the results of six representative models (M1-M6) for each of which isolated, interaction, and merging case are investigated. These models show typical behaviors in the star formation histories of very low-mass dwarf galaxies. The model M1 is the fiducial model, and the comparative models M7 and M8 are those in which there are no old stars (“starless” or “dark galaxies”). Table 1 summarized the model parameters for these eight models. Thilker et al. (2007) showed that if a star-forming region of a star cluster (or of a galaxy) has its SFR less than a threshold SFR, it can not be detected as a Hα source. The threshold SFR is defined as (Thilker et al. 2007):

$$\text{SFR}_{\text{th}}(\text{H} \alpha) = 10^{-5} M_\odot \text{yr}^{-1}. \quad (1)$$

We adopt this value in order to discuss whether a simulated galaxy can be detected as a Hα (star-forming) object.

### 3 RESULTS

Fig. 1 shows that star formation can be ignited as dwarf-dwarf interaction starts ($T > 0.13$ Gyr) in the fiducial merger model M1 with $M_\text{h} = 10^8 M_\odot$. The SFR during dwarf-dwarf interaction and merging can be significantly higher than $10^{-5} M_\odot$ yr$^{-1}$ (=SFR$_{\text{th}}$(Hα)) at $T = 0.28$ Gyr in this model, and only one of the interacting galaxies can host a compact H II region. The total stellar mass of new stars ($M_\star$) at $T = 0.28$ Gyr is only $3.1 \times 10^8 M_\odot$, and the stellar envelopes of old stars in the dwarfs have surface densities that are by a factor of $\sim 100$ lower than that of the Galaxy. Furthermore, the mergers of the present models show that $R_{25}$ (where $B-$band surface brightness is 25 mag arcsec$^{-2}$) is less than 100 pc. Therefore this star-forming object in M1 is unlikely to be detected as a faint galaxy like blue diffuse dwarfs (e.g., James et al. 2015), if its distance is more than 20 Mpc; it could be identified as a point-source (< 1") at such a distance. This object with a H II region can be identified as an isolated emission line object (EL-dot). The merger remnant at $T = 0.56$ Gyr also has two neighboring H II regions surrounded by young stars with $M_\star = 2.4 \times 10^8 M_\odot$. Although this low-luminosity remnant is also likely to be detected as an isolated EL-dot, it can be detected as an isolated gas cloud, if radio observations can detect its cold gas mass of $M_\text{g} \sim 10^9 M_\odot$.

After dwarf-dwarf merging, the remnant can slowly build up its central compact stellar system composed of new stars by converting the inflowing very metal-poor gas into stars ($T > 0.56$ Gyr). The SFR can be kept as high as $10^{-4} M_\odot$ so that the final $M_\star$ at $T = 1.1$ Gyr can be $1.0 \times 10^9 M_\odot$. As shown in Fig. 2, the typical metallicity of young stars is still low ($\log_{10} Z/Z_\odot \sim -1.1$) even after merging ($T > 0.56$ Gyr). Unlike major mergers between luminous galaxies, the low-mass dwarf-dwarf merging does not show rapid chemical enrichment owing to the very low
star formation efficiency (SFR/$M_\odot \sim 10^{-11} - 10^{-10}$ yr$^{-1}$) and SFR. As a result of this, the merger remnant can have stellar and gaseous metallicities that are only slightly higher than the initial values. These remnants can be detected as extremely metal-poor (i.e., $12+\log(O/H) < 7.65$), blue star-forming dwarfs when the central luminosities of young stars is high enough.

Fig. 2 shows that SFRs in the six isolated models are either zero or rather low ($< 10^{-9}$ M$_\odot$ yr$^{-1}$), which implies that these gas-rich, metal-poor dwarf in isolation are unlikely to be detected by recent emission-line surveys. The physical reason for this low SFR is that local and global dynamical instabilities, which can trigger galaxy-wide star formation, can be almost completely suppressed by the dominance of massive dark matter halos in these models ($f_b < 0.007$). These dwarfs, however, might be detected by UV observations (e.g., Meyer et al. 2015), if they have $\log_{10}$ SFR $> -5.5$ (e.g., Thilker et al. 2007) and if they are relatively nearby objects. Fig. 2 also shows SFRs can be higher than $10^{-5}$ M$_\odot$ yr$^{-1}$ only during and after dwarf-dwarf merging in the six representative models.

Although hyperbolic tidal interaction can significantly enhance SF in the models M1-M4 with $M_b = 10^9$ M$_\odot$, it can not ignite SF in low-mass models M5 and M6 with $M_b = 10^3$ M$_\odot$. These results imply that major merging is essential for such low-mass dwarfs to have a detectable amount of SF. The isolated model M3 with higher $f_b = 0.02$ can have SFRs that can be detected by emission whereas other models with lower $f_b$ show no or little SF in the isolated evolution. This result suggests that $f_b$ is a key parameter for SF histories of low-mass dwarfs in isolation. The remnants of low-mass dwarf-dwarf merging can continue their low-level SF, because new gas disks with higher gas densities can be developed after gas-rich merging. It is confirmed that minor dwarf-dwarf merging can show SFRs higher than $10^{-5}$ M$_\odot$ yr$^{-1}$, though the mean SFR can be significantly lower than major merging cases.

Fig. 3 shows that the remnant of dwarf-dwarf merging with $M_b = 10^3$ M$_\odot$, $f_b = 0.006$, and $f_g = 100$ has a very compact nucleus with $R_{25} = 51$ pc embedded by a very diffuse stellar envelope with $\mu_B > 30$ mag arcsec$^{-2}$ at $R > 200$ pc. The total mass of old and new stars are $6.3 \times 10^8$ M$_\odot$ and $2.3 \times 10^4$ M$_\odot$, respectively. The compact nucleus with the size well less than 100 pc can be classified as a low-mass globular cluster (GC) owing to the very low surface brightness envelope of old stars, if it is detected in photometric observations. Since the merger precursor galaxy in this model corresponds to an UFD, this result suggests that gas-rich UFDs can be transformed into low-mass “GCs” with stellar halos. These “GCs” (which are indeed nucleated UFDs with star formation) can have dark matter halos and therefore can be distinguished from normal GCs without dark matter. Since this transformation from UFDs into low-mass GCs is a serendipitous discovery in the present study, we need to explore the details of this transformation process in our future studies.

The comparative model M7 with no old stars and a low $f_b (\sim 6 \times 10^{-4})$ does not show any SF in isolated, interacting, and merging cases (thus not shown in Fig. 2). The compact gas cloud in the merger remnant embedded in a dark matter halo could be identified as a high velocity cloud (HVC) in a luminous galaxy like the Galaxy, when it enters inter the virial radius of the galaxy. The comparative merger model M8 with $f_b = 1.2 \times 10^{-3}$ shows low-level SF and after major merging whereas the isolated model M8 does not show any SF. These results for M7 and M8 imply that there would be a threshold $f_b$ above which star formation is re-activated through merging in low-mass halos.

4 DISCUSSION AND CONCLUSIONS

We have shown that extremely gas-rich, very faint dwarf (“almost dark”) galaxies are unlikely to have SFRs higher than $10^{-5}$ M$_\odot$ yr$^{-1}$, if they are in isolation. However, such almost dark galaxies can become star-forming objects with SFRs as high as $10^{-4}$ M$_\odot$ yr$^{-1}$ that is readily detected in recent Hα emission surveys (e.g., W10), when they interact or merge with other low-mass galaxies: These objects with very low-level SF transformed from almost dark galaxies might be dubbed as “cosmic fireflies”. The star-forming regions with SFRs much lower than $0.1 - 1$ M$_\odot$ yr$^{-1}$ are compact surrounded by very low surface brightness envelopes of old stars that can be hardly detected by optical observations. Therefore, such interacting/merging dwarfs with detectable SF are likely to be identified as isolated ELdots rather than starbursting BCDs.

After dwarf-dwarf interaction and merging, star formation can continue to occur at low level (SFR$\sim 10^{-4}$ M$_\odot$ yr$^{-1}$) in the star-forming low-mass dwarfs. The total mass of new stars ($M_{\text{new}}$) in the central compact component of the dwarfs can be large ($M_{\text{new}} > 10^5$ M$_\odot$) so that the central components can be detected as low-luminosity compact blue dwarfs. However, the mean stellar metallicities of the dwarfs are still rather low ($Z < 0.1 Z_\odot$). Therefore, such dwarfs are likely to be classified as XMD galaxies, if they are detected by optical and spectroscopic observations. The present study thus suggests that some of the observed XMD galaxies (e.g., Ekta et al. 2010; Skillman et al. 2013; James et al. 2015) can be the remnants of dwarf-dwarf interaction and merging. Given that a number of observational studies have recently started to search for very faint optical counterparts of compact HVCs (e.g., Adams et al. 2015; Janowiecki et al. 2015; Sand et al. 2015), these results provide the following
important implications on the origins of ELdots, compact HVCs, and XMD dwarfs.

First is that there could be two different types of ELdots with low and high metallicities. The present study predicts (i) that ELdots formed from interacting or merging low-luminosity dwarf galaxies show rather low metallicity ($Z < 0.1Z_\odot$) and (ii) that they might be surrounded by very low surface brightness old stellar components. Since ELdots formed from gas stripped from luminous disk galaxies (like NGC 1533) or in the very outer part of galactic gas disks are unlikely to show very low metallicities, the metallicities of ELdots might be a key to discriminate between different formation scenarios of ELdots. Also, very deep optical imaging of ELdots is doubtless worthwhile, because it would be able to reveal the very low surface-brightness components of low-mass dwarf galaxies.

Second is that interacting and merging low-mass dwarfs can be identified as compact HVCs with star formation. Recently, Stark et al. (2015) have revealed that there is an excess of OB stars along the line of sight to the Smith Cloud, which is one of the massive HVCs in the Galaxy. They suggested that the HVC has been forming stars since it passed through the Galaxy about 70 Myr ago. The present study suggests that the cloud is a very gas-rich low-mass dwarf galaxy with its star formation highly enhanced by the interaction with the Galaxy. It is, however, unclear why such a low-mass dwarfs can retain much gas now, since ram pressure stripping by the Galactic halo gas can remove all gas from such low-mass dwarf galaxies (Yozin & Bekki 2015).

Third is that some of the observed compact HVCs in the Galaxy and M31 (e.g., Westmeier et al. 2005) might be the remnants of ancient mergers between low-mass halos: Some compact HVCs are embedded in low-mass dark matter halos. The compact HVCs embedded in dark matter halo might be less susceptible to the ram pressure stripping by their host galaxies so that the central regions can survive from such stripping processes and thus can be identified as compact HVCs. As demonstrated in the present study, star formation is unlikely in dwarf-dwarf mergers with very low $M_\text{h}$ and $f_\text{h}$, though this might be due largely to the adopted simulation code with no efficient cooling below $T = 100\text{K}$. No/little star formation can prevent cold gas from thermal evaporation of energetic supernovae so that the merger remnants can be still observed as compact gas clouds.

Fourth is that the observed recent star formation in nearby very faint dwarf galaxies like Leo T (e.g., Ryan-Weber et al. 2008) and Leo P (e.g., Skillman et al. 2013) can be due to their recent interaction and merging with other low-mass faint dwarf galaxies. Fifth is that there can be numerous very faint dwarf galaxies (like UFDs) with very low-level star formation (SFRs well less than $10^{-3} M_\odot$ yr$^{-1}$) undetected in the present Hα observations. Gas-rich very faint dwarf galaxies located outside the Local Group might not be detected by current HI surveys either, if their gas masses are less than $10^5 M_\odot$. These almost dark dwarf galaxies will be able to be detected by future wide-field, ultra-deep HI observations by the Square Kilometre Array (SKA), if they really exist.

The present study suggests that there is an evolutionary link between almost dark galaxies, isolated ELdots, and XMD dwarfs. It should be noted here, however, that the present study assumed low-mass dark matter halos hosting very gas-rich dwarfs. Although a number of ongoing observational projects aim at detecting very gas-rich, low-mass dwarf candidates (e.g., Meyer et al. 2015), it is currently unclear whether there really exist numerous almost dark dwarfs in the universe: The observed almost dark galaxies could be just a rare class of dwarfs. If such galaxies are a major population in low-mass halos, then the present results imply that there could be much more isolated ELdots and XMD dwarfs at higher redshifts, when interaction and merging between low-mass halos is highly likely to be much more frequent.

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