EFFECTS OF DUST EXTINCTION ON OPTICAL SPECTROSCOPIC PROPERTIES FOR STARBURST GALAXIES IN DISTANT CLUSTERS

Yasuhiro Shioya
Astronomical Institute, Tohoku University, Sendai 980-8578, Japan

and

Kenji Bekki
Division of Theoretical Astrophysics, National Astronomical Observatory, Mitaka, Tokyo 181-8588, Japan

Received 2000 May 2; accepted 2000 June 30; published 2000 August 1

ABSTRACT

Recent observational studies on galaxies in distant clusters discovered a significant fraction of possible dusty starburst galaxies with the so-called e(a) spectra that are characterized by strong Hα absorption and relatively modest [O II] emission. We numerically investigate spectroscopic and photometric evolution of dusty starburst galaxies in order to clarify the origin of the e(a) spectra. We found that if a young starburst population is preferentially obscured by dust over an old one in a dusty starburst galaxy, the galaxy shows an e(a) spectrum. It is therefore confirmed that the selective dust extinction, which was first suggested by Poggianti & Wu and means that the strongest dust extinction occurs in the youngest among stellar populations with different ages, is critically important to reproduce quantitatively the observed e(a) spectra for the first time in the present numerical study. We also discuss what physical process is closely associated with this selective dust extinction in a cluster environment.

Subject headings: galaxies: clusters: general — galaxies: formation — galaxies: interactions — galaxies: ISM — galaxies: structure — infrared: galaxies

1. INTRODUCTION

Since Butcher & Oemler (1978) discovered a large fraction of blue galaxies in distant clusters of galaxies at the redshift \( z \geq 0.2 \), the origin of the blue color and physical processes closely associated with the formation of the distant blue populations have been extensively discussed by many authors (Dressler & Gunn 1983, 1992; Laevy & Henry 1986; Couch et al. 1994, 1998; Abraham et al. 1996; Barger et al. 1996; Fisher et al. 1998; Morris et al. 1998; Balogh et al. 1999). In particular, Dressler & Gunn (1983, 1992) discovered galaxies with no detectable emission lines and very strong Balmer absorption lines (the so-called E + A galaxies) and concluded that some fraction of distant blue populations are poststarburst galaxies that abruptly truncated their active star formation. One long-standing and remarkable problem concerning the evolution of galaxies in a cluster environment is to clearly understand a physical relationship between these blue populations, whose number fractions rapidly increase with redshift, and passive populations such as elliptical and S0 galaxies. Several attempts have been made to clarify an evolutionary link among star-forming, poststarburst, and passively evolving galaxies observed in distant clusters of galaxies (Couch & Sharples 1987; Abraham et al. 1996; Barger et al. 1996; Morris et al. 1998; Balogh et al. 1999). It is, however, not so clear whether there is really an evolutionary link among these populations with various spectroscopic properties and what physical process can drive the evolution.

Recent observational studies have found a significant population of possible dusty starburst galaxies in distant clusters (Poggianti et al. 1999; Owen et al. 1999; Smail et al. 1999), which provides a new clue to the evolutionary link among various spectral classes. Poggianti et al. (1999) suggested that galaxies with strong Balmer absorption and relatively modest [O II] emission, which are classified as e(a) galaxies by Dressler et al. (1999), are dusty starburst galaxies and, furthermore, concluded that distant clusters have a significant fraction of these dusty starburst galaxies. Smail et al. (1999) found that spectral properties of five out of 10 galaxies detected by 1.4 GHz Very Large Array radio observations are classified as poststarburst (a + k/k + a type in Dressler et al. 1999) and considered that the star formation is hidden by dust in them. This finding suggested that dust effects are remarkable even for galaxies that were previously identified as poststarburst by optical spectral properties. Although a growing number of observational results on e(a) galaxies with possible dusty starbursts have been accumulated, there are only a few theoretical studies addressing the formation and evolution of these e(a) populations in distant clusters.

The purpose of this Letter is to investigate the origin and the nature of the e(a) population observed in distant clusters of galaxies by using a one-zone chemical and spectrophotometric evolution model. We particularly investigate whether dusty starburst galaxies can show both strong Hα absorption and relatively modest [O II] emission observed in distant e(a) galaxies. We demonstrate that if a younger stellar population formed during a starburst is preferentially obscured by dust in a galaxy, spectral properties of the galaxy during a starburst become very similar to those characteristics of e(a) populations. We refer to this behavior of dust extinction as selective dust extinction, which was originally proposed by Poggianti & Wu (2000) and means that the effect of dust extinction is maximum for the youngest stellar populations among stellar populations with different ages. We furthermore suggest that this selective extinction can be achieved in interacting and merging galaxies in distant clusters. In the following, the cosmological parameters \( H_0 \) and \( q_0 \) are set to be 65 km s \(^{-1}\) Mpc \(^{-1}\) and 0.05, respectively, which means that the corresponding present age of the universe is 13.8 Gyr.

2. MODEL

We adopt a one-zone chemical and spectrophotometric evolution model of a disk galaxy with a starburst and thereby
investigate when and how a disk galaxy shows a strong H$\alpha$ absorption line and relatively modest [O II] emission line characteristics of e(a) spectra observed in distant clusters of galaxies. Since more details of the adopted one-zone model are given in Shioya & Bekki (1998), we only briefly describe the model in the present study. We follow the chemical evolution of galaxies by using the model described in Matteucci & Tornambe (1987), which includes metal-enrichment processes of Type Ia and II supernovae. We adopt the Salpeter initial mass function, $\phi(m) \propto m^{-1.35}$, with an upper mass limit $M_{\text{up}} = 120M_\odot$ and a lower mass limit $M_{\text{low}} = 0.1M_\odot$. We calculate photometric properties of galaxies as follows. The monochromatic flux of a galaxy with age $T$, $F_\lambda(T)$, is described as

$$F_\lambda(T) = \int_0^T F_{\text{SSP},\lambda}(Z, T-t)\psi(t)dt,$$

(1)

where $F_{\text{SSP},\lambda}(Z, T-t)$ is a monochromatic flux of a single stellar population with age $T-t$ and metallicity $Z$, and $\psi(t)$ is the time-dependent star formation rate (SFR) described later. The time $t$ in equation (1) represents the time that has elapsed since galactic star formation begins. In the present study, we use the spectral library GISSEL96, which is the latest version of Bruzual A. & Charlot (1993).

The star formation history of a disk galaxy is characterized by three epochs. The first is the epoch of galaxy formation ($z_{\text{form}}$ is redshift, and the age of the galaxy is 0 Gyr) at which a disk galaxy forms and begins to consume initial interstellar gas by star formation at a moderate rate. In the present study, $z_{\text{form}}$ is fixed at 4.5. The second is $z_{\text{end}}$, at which starburst begins in the disk. In the present study, $z_{\text{end}}$ is set to 0.4, and the age of galaxies at $z_{\text{end}}, T_{\text{end}}$, is 7.64 Gyr. We adopted these values in order that a disk galaxy has the age of 12 Gyr at $z = 0$ and can experience starburst with a relatively large gas fraction ($>0.2$) at distant clusters ($0.1 < z < 1.0$). The third is $z_{\text{end}}$, at which star formation ceases, and is defined as the epoch at which the stellar mass fraction becomes 0.95 in our models. The age of galaxies at $z_{\text{end}}, T_{\text{end}}$, is 8.56 Gyr. In the following, we use mainly the age of galaxies to describe their evolution. Throughout the evolution of disk galaxies, the SFR is assumed to be proportional to the gas mass fraction ($f_g$) of galaxies:

$$\psi(t) = kf_g,$$

(2)

where $k$ is a parameter that controls the SFR. This parameter $k$ is given as follows:

$$k = \begin{cases} k_{\text{disk}} & \text{for } 0 \leq T < T_{\text{sh}}, \\ k_{\text{sbf}} & \text{for } T_{\text{sh}} \leq T < T_{\text{end}}, \\ 0 & \text{for } T_{\text{end}} \leq T. \end{cases}$$

(3)

In the following, we refer to the first, second, and third phases as prestarburst, starburst, and poststarburst, respectively. In the present study, we set the value of $k_{\text{disk}}$ to 0.225 Gyr$^{-1}$, which corresponds to a plausible SFR for Sb disk galaxies (e.g., Arimoto, Yoshii, & Takahara 1992); $k_{\text{sbf}}$ is considered to be 10 times larger than $k_{\text{disk}}$ (2.25 Gyr$^{-1}$), which is consistent with observational results of starburst galaxies (e.g., Planesas, Colina, & Perez-Olea 1997). Figure 1 shows the star formation history of our model.

We try to understand the role of selective dust extinction in the formation of e(a) galaxies by comparing the following two models with each other: a model with no dust extinction (ND model) and the selective dust extinction model (SD model). In the ND model, dust effects on photometric and spectroscopic properties are completely neglected; i.e., $A_V = 0$ at all times. In the SD model, we assume that during starburst the value of $A_V$ depends on the age of stellar population; i.e.,

$$A_V = A_{V,0}\exp \left[\left(T - t\right)/\tau\right] \text{ for } T_{\text{sh}} < T < T_{\text{end}},$$

(4)

where $A_{V,0}$ and $\tau$ are parameters controlling the degree of extinction. Here we adopt $A_{V,0} = 5$ mag and $\tau = 1.0 \times 10^6$ yr, and the adopted value is reasonably consistent with the observational values suggested by Smail et al. (1999) for dusty starburst galaxies in distant clusters. Based on the monochromatic flux derived in equation (1) and the value of $A_V$ from equation (4) for each age of a galaxy $T$, we calculated the spectral energy distribution (SED) of a galaxy corrected by dust extinction using the extinction law derived by Cardelli, Clayton, & Mathis (1989) and adopting the so-called screen model. To derive the fluxes for various gaseous emission lines (H$\beta$ and [O II]) in dusty starburst galaxies, we first calculate the number of Lyman continuum photons $N_{\text{Ly}}$ by using the SED that is not modified by dust extinction.

If all Lyman continuum photons are used for ionizing the surrounding gas, the luminosity of H$\beta$ is calculated according to the following formula:

$$L(\text{H}\beta) \text{ (ergs s}^{-1}) = 4.76 \times 10^{-13}N_{\text{Ly}} \text{ (s}^{-1})$$

(Leitherer & Heckman 1995). To calculate luminosities of other emission lines, e.g., [O II] and H$\alpha$, we use the relative luminosity to H$\beta$ luminosity tabulated in PEGASE (Fioc & Rocca-Volmerange 1997), which is calculated for the set of electron temperature 10,000 K and electron density 1 cm$^{-3}$. Thus, the SED derived in the present study consists of stellar continuum and gaseous emission.

3. RESULTS

The time evolution of EW(H$\beta$) and EW([O II]) for the ND and SD models is shown in Figure 2. First, we describe the
The evolution of the equivalent width of Hα evolves as follows. During the prestarburst evolution phase, the Hα line is observed as an absorption line. A few times $10^8$ yr after the starburst begins, the equivalent width of Hα becomes large. This is because the flux of Hα emission line becomes large. The equivalent width of Hα decreases and becomes very large just after the starburst begins. Although the Hα line is still observed as an absorption line, a few times $10^8$ yr after the starburst begins, the equivalent width of Hα becomes less than 4 Å. The reason the equivalent width of Hα in the SD model is always larger than that of the ND model is that the flux of Hα emission line of the SD model is smaller than that of the ND model.

Figure 3 shows the evolution of galaxies on the $EW([O\ II])-EW(H\delta)$ plane for each model. The criteria of spectroscopic classification determined by Dressler et al. (1999) are superimposed on it. The ND model is located within the e(b) region during starburst and very rapidly shifts to the a region just when the starburst ends. Although the locus of the ND model passes through the e(a) region, the crossing time is about 0.5% of the duration of the starburst. On the other hand, the SD model can successfully show the spectroscopic properties of e(a) galaxies, namely, a strong Hα absorption line $[EW(H\alpha) > 4$ Å] and a relatively modest $[O\ II]$ emission line $[5$ Å $< EW([O\ II]) < 40$ Å] during the most of the starburst phase (0.7 Gyr). These results suggest that selective extinction plays a vital role in the formation of galaxies with e(a) spectra and thus confirm the early suggestion by Poggianti & Wu (2000) that if the youngest stellar population is the most heavily obscured by dust in a dusty starburst galaxy, e(a) spectra can be achieved in the galaxy.
As described above, we have confirmed that the SD model shows the weaker [O II] emission and stronger Hδ absorption compared with the ND model. The physical reason for the successful reproduction of the SD model can be understood in terms of the difference in the influence of dust extinction between continuum and emission lines. The emission lines come from the ionized gas around the youngest stellar populations, which are most heavily obscured by dust. On the other hand, most of the continuum comes from the stellar populations that are older and less obscured than the younger ones dominating the ionizing photons. The flux of emission lines is consequently more greatly affected by dust extinction than that of the stellar continuum. Thus, the SD model can show the smaller equivalent width of emission lines without greatly changing the continuum flux.

4. DISCUSSION AND CONCLUSIONS

Although the essentially important effects of selective dust extinction in the formation of e(a) galaxies do not depend so strongly on model parameters of the present study for a plausible range of the parameters, the location of starburst disks on the EW([O II])-EW(Hδ) plane are appreciably different between models with different parameters. We accordingly summarize the following three parameter dependences on A_v_0, τ, T_d, k_disk, and k_abs (additional details of the dependences and the physical reasons for the dependences will be described in our future papers). First, a galaxy with larger A_v_0 is located in the lower and farther right e(a) region during a dusty starburst for a plausible range of 1.0 ≤ A_v_0 ≤ 10.0. Second, a dusty starburst galaxy with larger τ has a lower EW([O II]) value and a higher EW(Hδ) value [i.e., is located in the lower and farther right e(a) region]. Third, a disk galaxy with the longer starburst timescale (with smaller k_disk) does not pass through the a + k region after the e(a) phase and thus evolves quickly into the k + a + galaxy after the dusty starburst. The dependences on T_d and k_disk are very complicated, and we will describe them in future papers. Poggianti et al. (1999) have already suggested a possible evolutionary sequence that a dusty starburst galaxy evolves from e(b) to e(a) to k + a/k and finally to k. Figure 3 of the present study confirms this sequence, and the above three parameter dependences suggest that the sequence depends weakly on the degree of dust extinction, the star formation history, and the duration of the starburst. We note here that even if we change rather greatly the model parameters, we do not reproduce spectroscopic properties of galaxies with very large EW([O II]) and EW(Hδ). Those galaxies may have active galactic nuclei and a larger [O II]/Hδ ratio than that of the Hδ region that we adopt in our model.

Poggianti & Wu (2000) first suggested that if the location and thickness of dust patches depend on the age of the embedded stellar populations in a starburst galaxy, the effects of the above selective dust extinction become remarkable for the galaxy. Then, when and how is the proposed difference in the degree of dust extinction between stellar populations with different ages possible during galactic evolution in distant clusters? Here we suggest that the difference of dust extinction between the central and outer regions in a galaxy is a main cause for the above age-dependent extinction. To be more specific, since younger stellar populations formed by a secondary starburst in the central region with a larger amount of dusty interstellar gas are more heavily obscured by dust than the outer old components, age-dependent extinction can be achieved. This radial dependence of dust extinction is considerably reasonable and realistic, considering that a secondary dusty starburst occurs preferentially in the central part of a galaxy owing to efficient inward gas transfer driven by nonaxisymmetric structure (such as stellar bars) and galaxy interaction and merging. Numerical simulations of gaseous and stellar distribution in merging disk galaxies with a dusty starburst have furthermore demonstrated that the central young stellar component formed by a nuclear starburst is more heavily obscured by dusty gas than the outer old component initially located in merger progenitor disks (Bekki, Shioya, & Tanaka 1999). Thus, we strongly suggest that galaxies with a central dusty starburst are more likely to show selective dust extinction. Future observational studies on the radial dependence of photometric and spectroscopic properties for e(a) galaxies, which can reveal the detailed distribution of a young dusty population and that of an old one with less extinction, will assess the validity of the above idea for the origin of selective dust extinction (i.e., age-dependent extinction).

We are grateful to the anonymous referee for valuable comments, which improved the present Letter. Y. S. thanks the Japan Society for Promotion of Science (JSPS) Research Fellowships for Young Scientists.

REFERENCES

Abraham, R. G., et al. 1996, ApJ, 471, 694
Arimoto, N., Yoshii, Y., & Takahara, F. 1992, A&A, 253, 21
Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., &Ellis, E. S., 1997, ApJ, 527, 54
Barger, A. J., Aragón-Salamanca, A., Ellis, R. S., Couch, W. J., Smail, I., & Shapley, R. 1996, MNRAS, 279, 1
Bekki, K., Shioya, Y., & Tanaka, I. 1999, ApJ, 520, L99
Bruszual A., & Charlot, S. 1993, ApJ, 405, 538
Butcher, H., & Oemler, A., Jr. 1978, ApJ, 219, 18
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Couch, W. J., Barger, A. J., Smail, I., Ellis, R. S., & Shapley, R. M. 1998, ApJ, 497, 188
Couch, W. J., Ellis, R. S., Shapley, R. M., & Smail, I. 1994, ApJ, 430, 121
Couch, W. J., & Shapley, R. M. 1987, MNRAS, 229, 423
Dressler, A., & Gunn, J. E. 1983, ApJ, 270, 7
———. 1992, ApJS, 78, 1
Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., & Oemler, A., Jr. 1999, ApJS, 122, 51
Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950
Fisher, D., Fabricant, D., Franx, M., & van Dokkum, P. 1998, ApJ, 498, 195
Lavery, R. J., & Henry, J. P. 1986, ApJ, 304, L5
Leitherer, C., & Heckmann, T. M. 1995, ApJS, 96, 9
Matteucci, F., & Tornambé, A. 1987, A&A, 185, 51 (erratum 196, 341 [1988])
Morris, S. L., Hutchings, J. B., Carlberg, R. G., Yee, H. K. C., Ellingson, E., Balogh, M. L., Abraham, R. G., & Smecker-Hane, T. A. 1998, ApJ, 507, 84
Owen, F. N., Ledlow, M. J., Keel, W. C., & Morrison, G. E. 1999, AJ, 118, 633
Planesas, P., Colina, L., & Perez-Olea, D. 1997, A&A, 325, 81
Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, J., Butcher, H., Ellis, E. S., & Oemler, A., Jr. 1999, ApJ, 518, 576
Poggianti, B. M., & Wu, H. 2000, ApJ, 529, 157
Shioya, Y., & Bekki, K. 1998, ApJ, 504, 42
Smail, I., Morrison, G., Gray, M. E., Owen, F. N., Ivison, R. J., Kneib, J.-P., & Ellis, R. S. 1999, ApJ, 525, 609