Formation and evolution of E+A galaxies in dusty starburst galaxies

Kenji Bekki

School of Physics, University of New South Wales, Sydney 2052, Australia

Yasuhiro Shioya

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

and

Warrick J. Couch

School of Physics, University of New South Wales, Sydney 2052, Australia

Received ____________________; accepted ____________________

ABSTRACT

The formation and evolution of the "E+A" (also named "k+a" and "a+k" types by Dressler et al. 1999) galaxies found in significant numbers in the cores of intermediate redshift clusters has been extensively discussed by many authors. In this paper, we model the spectral, dynamical and morphological evolution of a prime candidate for producing this spectral signature: a dusty starburst associated with a major galaxy merger. We show that as this system evolves dynamically, its spectral type changes from and "e(a)" type (exhibiting strong Hδ absorption and modest [OII] emission – the identifying features of local dusty starburst galaxies) to a k+a type and then finally to a passive "k" type. This result shows that galaxies with an e(a) spectral type can be precursors to the k+a systems and that dynamical evolution greatly controls the spectral evolution in these merger cases. Our simulations also show that a merger with very high infrared luminosity ($L_{\rm IR} > 10^{11}\ L_{\odot}$) is more likely to show an e(a) spectrum, which implies that spectral types can be correlated with infrared fluxes in dusty starburst galaxies. Based on these results, we discuss the origin of the evolution of k+a/a+k galaxies in distant clusters and the role merging is likely to have.

Subject headings: galaxies: clusters: general — galaxies: ISM — galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: interactions

1. Introduction

The origin of the so-called “E+A” galaxies with no detectable emission and strong Balmer absorption lines, is generally considered to be one of the most longstanding and remarkable problems of galaxy evolution in distant ($z > 0.2$) clusters. Dressler & Gunn (1983) proposed that this peculiar spectroscopic property was due to the presence of a substantial population of A-type stars, having been formed as part of a recent starburst which was abruptly truncated. Since Couch & Sharples (1987) suggested a possible evolutionary link between these E+A galaxies and the general population of blue galaxies found in distant clusters (Butcher & Oemler 1978), several attempts have been made to determine what physical processes are closely associated with the abrupt truncation of star formation that is inferred from their spectral characteristics (e.g., Abraham et al. 1996; Barger et al. 1996; Balogh et al. 1997; Couch et al. 1998; Poggianti et al. 1999). Although the formation of E+A galaxies has been often discussed in terms of physical processes specific to the cluster environment, Zabludoff et al. (1996) found that a large fraction of nearby E+A galaxies lie in the field rather than in clusters and therefore suggested that cluster environmental effects such as interaction with the cluster gravitational potential or intracluster medium are not responsible for E+A formation.

Recent detailed morphological and spectroscopic studies by the *Hubble Space Telescope* (*HST*) and large ground–based telescopes have shed new light on the origin of E+A galaxies. For example, a significant fraction of the distant cluster galaxies with E+A spectra – renamed by Dressler et al. (1999) as “a+k” or “k+a” types – are observed to be disk systems, which implies that abrupt (or even gradual) truncation of star formation (after the starburst) has occurred without a dramatic transformation in their morphology (Couch et al. 1998; Dressler et al. 1999). Furthermore, Poggianti et al. (1999) argued on the basis of the observed fractions and luminosity functions of the different spectral types that the progenitors of a+k/k+a galaxies were the "e(a)" class objects – those with modest [OII] emission and strong Balmer line absorption [EW(Hδ) > 4Å], the same two features that characterize the spectra of nearby dusty starburst galaxies (Liu & Kennicutt 1995). These observational results strongly suggest that it is very important for theoretical studies to address the following three problems: (1) What are the physical processes responsible for the formation of E+A galaxies? (2) What are the evolutionary links between the different spectral types, in particular the e(a), e(b), e(c), a+k, k+a, and k class objects identified by Dressler et al. (1999)? (3) How is the observed morphological evolution (e.g., the smaller fraction of S0 populations in higher redshift clusters; Dressler et al. 1997) related to spectral evolution of galaxies in clusters? Clearly both the morphological and spectral properties of distant cluster galaxies have to be investigated *jointly* in a fully self-consistent manner if these questions are to be answered. However, previous theoretical studies have investigated quite separately the morphological transformation processes (using numerical methods; Byrd & Valtonen 1990; Moore et al. 1994) and the possible spectral evolutionary links (using simple one-zone models; Barbaro & Poggianti 1997; Poggianti et al. 1999; Shioya & Bekki 2000). Thus, it is still highly uncertain when and how E+A galaxies form and evolve both spectrally and morphologically.

The purpose of this Letter is to investigate the morphological, photometric, and spectroscopic properties of galaxies in an explicitly self-consistent manner and thereby provide some plausible and realistic answers to the above three problems. We adopt an observationally suggested scenario that *some* E+A galaxies are formed by strong interactions and merging (e.g., Zabludoff et al. 1996), and demonstrate when and how a dusty starburst triggered by a major galaxy merger develops an E+A spectrum in the course of its dynamical evolution. Here we use our newly developed model (Bekki & Shioya 2000, hereafter referred to as BS) by which we can self-consistently investigate the time evolution of spectral types (e.g., k+a, a+k, e(a)... etc), infrared fluxes (e.g., $L_{\rm IR}$ for 8−1000 μm), and dynamical properties (e.g., radial density profile) in a galaxy with dusty starbursts. Based on our new 'spectrodynamical' simulations (BS), we particularly demonstrate that a merger exhibits a k+a/a+k spectrum following its strong starburst phase and, furthermore, that the dynamical evolution of a galaxy can greatly control its spectral evolution.

2. The model

Since our numerical methods and techniques for modeling chemodynamical and photometric evolution of dusty starbursts associated with major galaxy mergers have already described in detail by BS, we give only a brief review here. We construct models of galaxy mergers between gas-rich disks with equal mass by using the model of Fall-Efstathiou (1980). The total mass and the size of a progenitor exponential disk are $M_{\rm d}$ and $R_{\rm d}$, respectively. From now on, all the mass and length are measured in units of $M_{\rm d}$ and $R_{\rm d}$, respectively, unless otherwise specified. Velocity and time are measured in units of $v = (GM_{\rm d}/R_{\rm d})^{1/2}$ and $t_{\rm dyn} = (R_{\rm d}^3/GM_{\rm d})^{1/2}$, respectively, where G is the gravitational constant and assumed to be 1.0 in the present study. If we adopt $M_{\rm d} = 6.0 \times 10^{10}$ $\rm M_{\odot}$ and $R_{\rm d}$ = 17.5 kpc as a fiducial value, then $v = 1.21 \times 10^2$ km/s and $t_{\rm dyn} = 1.41 \times 10^8$ yr, respectively. The disk-to-dark halo mass ratio is set equal to 4.0. The total mass of gas is 3.0×10^{10} $\rm M_{\odot}$. The orbital configuration of the present major merger between the above two disks is exactly the same as that in BS. To calculate spectral energy distributions (SEDs) of the merger and luminosities of gaseous emission lines, e.g., [OII] and Hδ, we use the spectral library GISSEL96 (Bruzual & Charlot (1993) and the formula of $L({\rm H}\beta)({\rm erg\ s^{-1}}) = 4.76 \times 10^{-13} N_{\rm Ly}({\rm s^{-1}})$, where $N_{\rm Ly}$ is ionizing photon production rate, and the table of relative luminosity to Hβ luminosity in PEGASE (Fioc & Rocca-Volmerange 1997). We investigated both a model without dust (referred to as "DF" for dust free) and a model with dust ("DS" or dusty starburst).

EDITOR: PLACE FIGURE 1 HERE.

EDITOR: PLACE FIGURE 2 HERE.

3. Results

Figure 1 describes the time evolution of EW([OII]) and EW(Hδ) of the merger-induced starburst over the period $0.6 \leq T \leq 2.8\,\mathrm{Gyr}$ for the DF and the DS models. At the point where the star formation rate rapidly increases ($T \sim 1.3\,\mathrm{Gyr}$), EW([OII]) is also seen to rapidly increase ($100 \leq$ EW([OII]) ≤ 370Å) in the DF model. In contrast, the DS model does not show such a dramatic increase during the starburst phase owing to the very heavy dust extinction. The DS model shows EW([OII]) does not exceed 40Å and the difference in EW([OII]) between the two models is rather large, ranging from a factor of ~ 3 at $T = 1.1\,\mathrm{Gyr}$ to a factor of 35 at $T = 1.3\,\mathrm{Gyr}$. After the starburst ($T > 1.3\,\mathrm{Gyr}$), EW([OII]) rapidly decreases with time for the two models.

Owing to the heavy dust extinction, EW(Hδ) does not show a large negative value during the starburst and is reasonably well within the observed values (< 10 Å; Liu & Kennicutt 1995) of dusty starburst galaxies for the DS model. The most important point in EW(Hδ) evolution is that only the DS model shows an absorption line signature (i.e., positive values) during the starburst and poststarburst epochs: *Dust effects are critically important for the EW(Hδ) evolution in dusty galaxies!*

Figure 2 demonstrates that as a natural result of the above EW([OII]) and EW(Hδ) evolution, the spectral type of the DS model evolves from e(b) ($T = 0.6\,\mathrm{Gyr}$), to e(a) (1.3), to k+a (1.7), and finally to k (2.8). This result confirms that a dusty starburst associated with a major merger can become a k+a galaxy ~ 0.4 Gyr after its burst of star formation.

One of the remarkable differences in the spectral evolution on the EW([OII])-EW(Hδ) plane between the two models is that only the DS model shows the e(a) spectral signature to persist for any length of time (~ 0.3 Gyr) during the period of active star formation. This result suggests that formation of e(a) galaxies is closely associated with dust extinction, thus confirming the earlier suggestion by Poggianti et al. (1999) and Shioya & Bekki (2000). Furthermore, as is shown in Figure 3, our modeling approach allows us to clearly observe the different morphological phases of the merger and to track the changes in spectral type in tandem through each. For the e(b) spectral phase, two tidally interacting disks are clearly observed whereas for the e(a) spectral phase, only a morphologically peculiar galaxy with clear signs of merging (a tidal dwarf and a very diffuse plume-like structure) can be seen. For the k+a/k phases, the merger becomes almost dynamically relaxed and thus does not show any clear relic of the past merging event(s). These results imply that the observed fraction of mergers among a+k/k+a (i.e., E+A) galaxies (e.g., Zabludoff et al. 1996) can actually be underestimated.

Figure 4 clearly shows an interesting physical correlation between the evolution in the infrared luminosity ($L_{\rm IR}$) and that seen in Hα emission. To be more specific, as the $L_{\rm IR}$ becomes higher, Hα emission becomes also stronger during the evolution in the DS model. The present model furthermore shows the larger difference in Hα luminosity between the two models (DF and DS) when the $L_{\rm IR}$ becomes higher (e.g., a factor of 100 difference for T = 1.3 Gyr). Considering the results given in Figure 2, these results suggest that (1) a dusty starburst merger with an e(a) spectrum can exhibit very high $L_{\rm IR}$ ($> 10^{11}$ $L_{\odot}$), but (2) this might not necessarily be accompanied by a high luminosity in Hα. The first of these suggestions is consistent with recent observations of infrared luminous e(a) galaxies by Poggianti & Wu (2000). The second means that even Hα observations can considerably underestimate (by a factor of ~ 100) the real star formation rate of a dusty starburst galaxy, and therefore infrared observations are much better for inferring the true star formation rate. Thus our spectrodynamical model has not only succeeded in providing an evolutionary link between galaxies with different spectral types (e.g., e(a) and k+a) but has also suggested physical correlations between spectral types, morphological properties, and infrared fluxes.

EDITOR: PLACE FIGURE 3 HERE.

EDITOR: PLACE FIGURE 4 HERE.

4. Discussion and conclusion

Our numerical results prompt the following question: can major galaxy merging account for the observation that the fraction of k+a/a+k galaxies in distant clusters (10-20% at $z \sim 0.4$; e.g., Dressler et al. 1999) is an order of magnitude higher than the fraction observed in low redshift clusters? From their own observations of the cluster MS1054-03 at $z = 0.83$ together with data taken from studies at lower redshift, van Dokkum et al. (1999) showed that the fraction of interacting/merging galaxies evolved very rapidly with redshift as $(1+\mathrm{z})^{6\pm2}$ over the interval $0 \le z \le 0.83$. By using this observed relation and assuming (i) that it refers to *major* mergers, and (ii) that all these mergers evolve spectrally to become k+a/a+k galaxies, the expected fraction of k+a/a+k galaxies (f_{k}) is found to be 7.5 % ($3.8\% \le f_{\mathrm{k}} \le 14.8\%$) at $z = 0.4$. The expected value is similar to the observed one (10-20%), which is consistent with major merging being the physical mechanism which drives the rapid evolution of the k+a/a+k population (We here stress that since the merger rate at high redshift is estimated only for the *single* $z = 0.83$ cluster, the expected merger rate at intermediate redshift is not so reliable). However, this conclusion is strongly countered by the observation that a significant fraction of the k+a/a+k types are *disk* systems (e.g., See Figure 10 in Dressler et al. 1999) – an unlikely candidate for the type of system likely to be produced in a major merger! Indeed, only a *minor* merger would seem capable of keeping the disk component intact. Thus, considering the observed redshift evolution of merger rates, that of a+k/k+a populations, and the dependence of the morphological transformation processes on the mass ratio of the two merging disks, it would seem that major merging can explain the origin of only a small fraction of the k+a/a+k population.

We have found that dusty starburst galaxies with e(a) spectra are plausible precursors to a+k/k+a galaxies. This raises a further question: what fraction of the k+a/a+k galaxies observed in distant clusters were previously starburst galaxies with e(a) spectra? Although a comparison of the fraction of e(a) galaxies with that of k+a/a+k types gives a rough estimate of the fraction of k+a/a+k galaxies which have evolved from e(a) galaxies (Couch & Sharples 1987; Barger et al 1996; Poggianti et al. 1999), the dusty nature of starburst galaxies makes this estimation considerably inaccurate. For example, based on the detection of some k+a galaxies by 1.4 GHz VLA radio observations, Smail et al. (1999) suggested that even k+a galaxies classified by EW([OII]) and EW(Hδ) can be dusty starburst galaxies. Hence more accurate observational estimation of star formation rate is necessary for answering the above question.

Couch et al. (2000) have investigated the incidence of Hα emission – considered to be much less affected by dust than [OII] emission – in members of the cluster AC114 at $z = 0.32$ and found that the star formation rate in the $\sim 5\%$ of galaxies so found to be strongly and uniformly suppressed (less than 4 $M_{\odot}$ yr^{-1}) right throughout the cluster ($r < 2.25\, h_{50}^{-1}$ Mpc). Balogh & Morris (2000) also investigated Hα emission from galaxies in Abell 2390 at z = 0.23 and also found the star formation rate inferred from Hα to be rather low. These observational studies strongly suggest that, unless the dust extinction is sufficient to totally obscure the Hα emission (which would require 4 magnitudes of extinction; Couch et al. 2000), the fraction of ongoing dusty starbursts must be very small, as would also be the fraction of galaxies which evolve from e(a) into k+a/a+k's. However, considering the observational evidence that the star formation rate inferred from Hα emission is a factor of 5–20 times smaller than that from far-infrared fluxes for strongly star-bursting dusty galaxies (e.g., Poggianti & Wu 2000), more systematic infrared and radio observations will be important for estimating the true fraction of ongoing starburst galaxies in distant clusters. It will only be the combination of systematic Hα, infrared, and radio observations that will unambiguously measure the star formation rate in dusty star-forming galaxies and this answer the question as to the origin of k+a/a+k galaxies.

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

Balogh M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1997, ApJ, 488, L75

Balogh M. L., & Morris, S. L. 2000, preprint (astro-ph/0007111)

Barbaro, G., & Poggianti, B. M. 1997, A&A, 490, 504

Barger A. J., Aragon-Salamanca, A., Ellis, R. S., Couch, W. J., Smail, I., & Sharples, R. M., 1996, MNRAS, 279, 1

Bekki, K., & Shioya, Y. 2000, ApJ, in press

Bruzual, A. G., & Charlot, S. ApJ, 405, 538

Butcher, H., & Oemler, A. ApJ, 226, 559

Byrd, G., & Valtonem, M., 1990, ApJ, 350, 89

Couch, W. J., & Sharples, R. M., 1987, MNRAS, 229, 423

Couch, W. J., Barger, A. J., Smail, I., Ellis, R. S., & Sharples, R. M. 1998, ApJ, 430, 121

Couch, W. J., Balogh, M. L., Bower, R. G., Smail, I., Glazebrook, K., & Taylor, M. 2000, submitted to ApJ

Dressler, A., & Gunn, J. E., 1983, ApJ, 270, 7

Dressler, A., et al. 1997, ApJ490, 577

Dressler, A., Smail, I., Poggianti, B. M., Butcher, H., Couch, W. J., Ellis, R. S., & Oemler, A., Jr. 1999, ApJS, 122, 51

Fall, S. M., & Efstathiou, G. 1980, MNRAS, 193, 189

Fioc, M., & Rocca-Volmerange, B. 1997, A&A, 326, 950

Kennicutt, R. C. 1989, ApJ, 344, 685

Liu, C. T., & Kennicutt, R. C., Jr. 1995, ApJ, 450, 547

Moore, B., Katz, N., Lake, G., Dressler, A., & Oemler, A. 1996, Nature, 379, 613

Poggianti, B. M., & Wu, H. 2000, ApJ, 529, 157

Poggianti, B. M., Smail, I., Dressler, A., Couch, W. J., Barger, J., Butcher, H., Ellis, E. S., & Oemler, A., Jr. 1999, ApJ, 518, 576

Shioya, Y., & Bekki, K. 2000, ApJ, 539, L29

Smail, I., Morrison, G., Gray, M. E., Owen, F. N., Ivison, R. J., Kneib, J.-P., & Ellis, R. S. 1999, ApJ, 525, 609

van Dokkum, P. G., Franx, M., Fabricant, D., Kelson, D. D., & Illingworth G. D. 1999, ApJ, 520, L95

Zabludoff, A. I., Zaritsky, D., Lin, H., Tucker, D., Hashimoto, Y., Shectman, S. A., Oemler, A. & Kirshner, R. P. 1996, ApJ, 466, 104

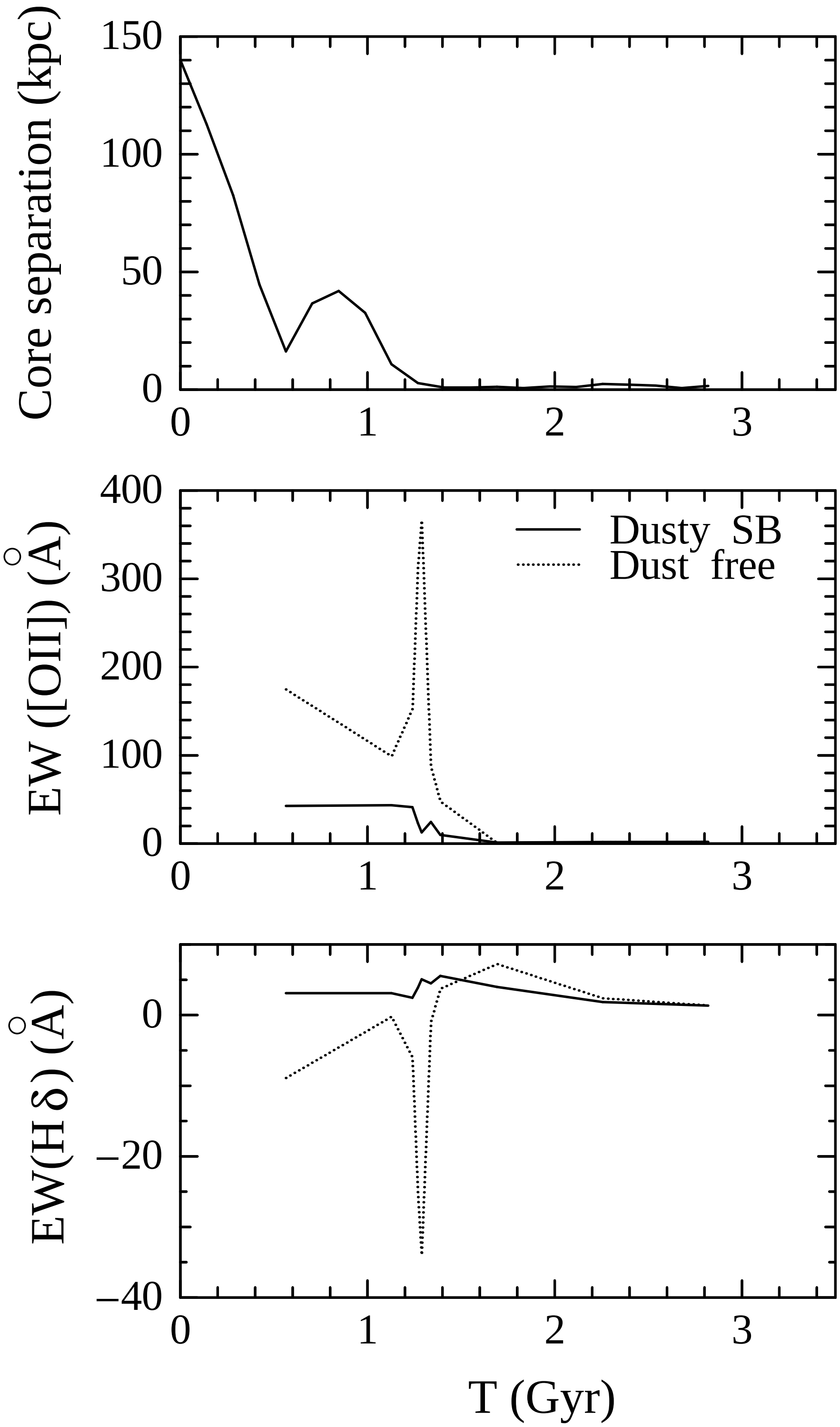
This manuscript was prepared with the AAS LaTeX macros v4.0.

Fig. 1.— *Top*: Time evolution of the core separation of two merging disks in units of kpc. Star formation rate becomes maximum ($\sim 3 \times 10^2\ M_\odot\ \mathrm{yr}^{-1}$) when the two cores (disks) finally merge to form a single core of an elliptical galaxy (T = 1.3 Gyr). Star formation is 0 $M_\odot\ \mathrm{yr}^{-1}$ at $T > 1.4$ Gyr when the two disks become an elliptical galaxy. *Middle*: Evolution of the equivalent width of [OII] emission line [EW([OII])]. The DF model (the dust free model, without dust extinction) and the DS one (the dusty starburst model, with dust extinction) are shown as the dotted and solid lines, respectively. Here the time T represents time that has elapsed since the two disks begin to merge. *Bottom*: Evolution of the equivalent width of Hδ [EW(Hδ)] for the DF model (dotted) and the DS one (solid).

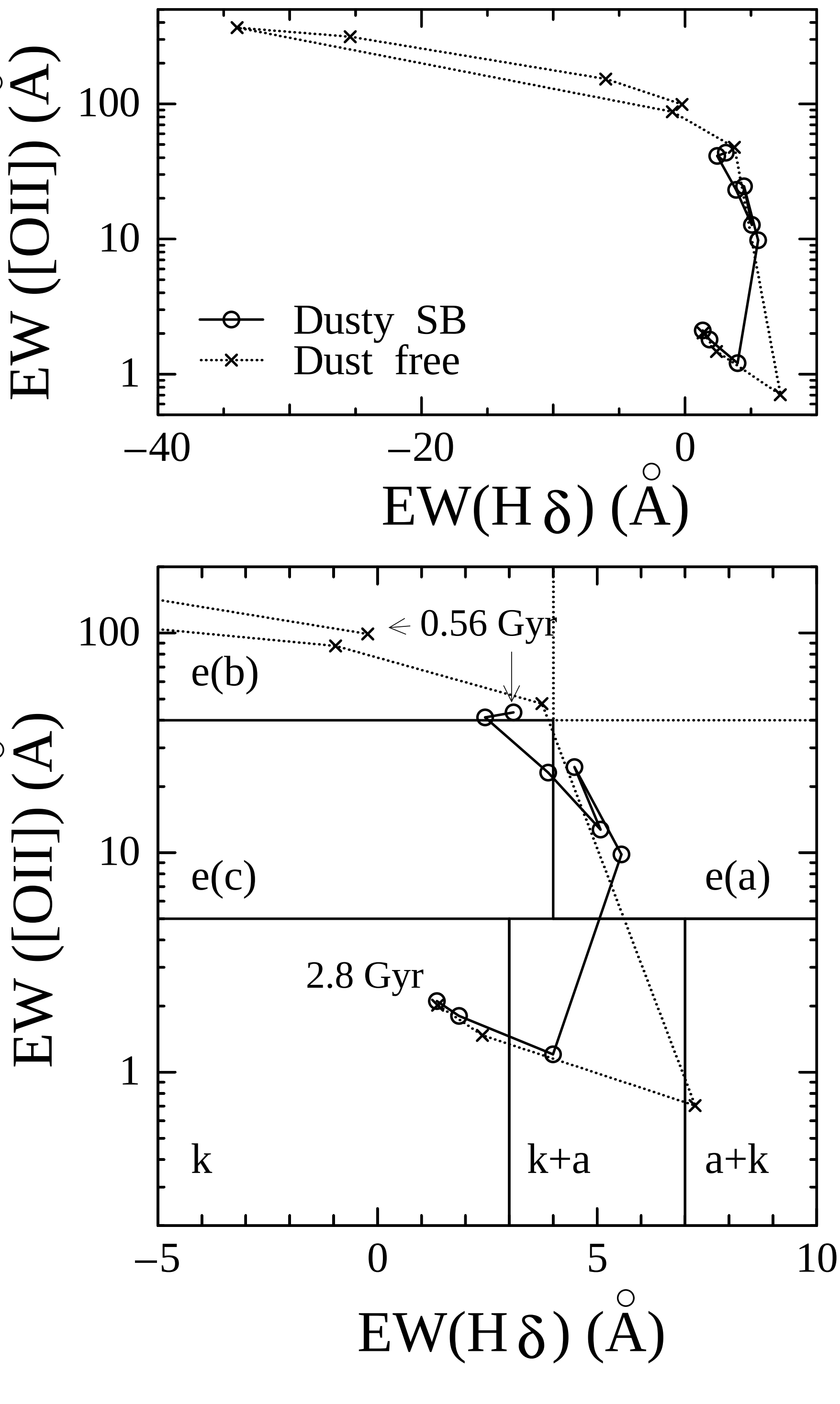
Fig. 2.— *Top*: Evolution of galaxies on the EW([OII])-EW(Hδ) plane for the ranges of $0 \leq$ EW([OII]) ≤ 500 Å and $-40 \leq$ EW(Hδ) ≤ 10 Å. The DF and DS models are shown as dotted and solid lines, respectively. The results at T = 0.56, 1.12, 1.24, 1.30, 1.34, 1.39, 1.69, 2.26, and 2.82 Gyr are given and connected with each other along the time sequence. *Bottom*: The same as the top panel but for the ranges of $0 \leq$ EW([OII]) ≤ 200 Å and $-5 \leq$ EW(Hδ) ≤ 10 Å. The criteria of spectral classification by Dressler et al (1999) are superimposed. For the two models, the initial (T = 0.56 Gyr) and final (2.82) spectral types are estimated to be e(b) and k, respectively. Note that only the DS model shows an e(a) spectrum for a fairly long time scale ($\sim$ 0.3 Gyr). Note also that the DS model evolves from e(b), to e(a), to k+a, and to k. This figure moreover demonstrates that if the effects of dust are negligible, the merger can show an a+k spectrum after undergoing a dusty starburst (Compare DF model with DS one).

Fig. 3.— Morphological properties and spectral types for the dusty starburst merger projected onto x-y plane at T = 0.56 Gyr (upper left), 1.30 (upper right), 1.69 (lower left), and 2.82 (lower right). Each frame measures 68.3 kpc on a side. Spectral types (e.g., e(a)) and time (T) are indicated in the upper left-hand corner for each frame.

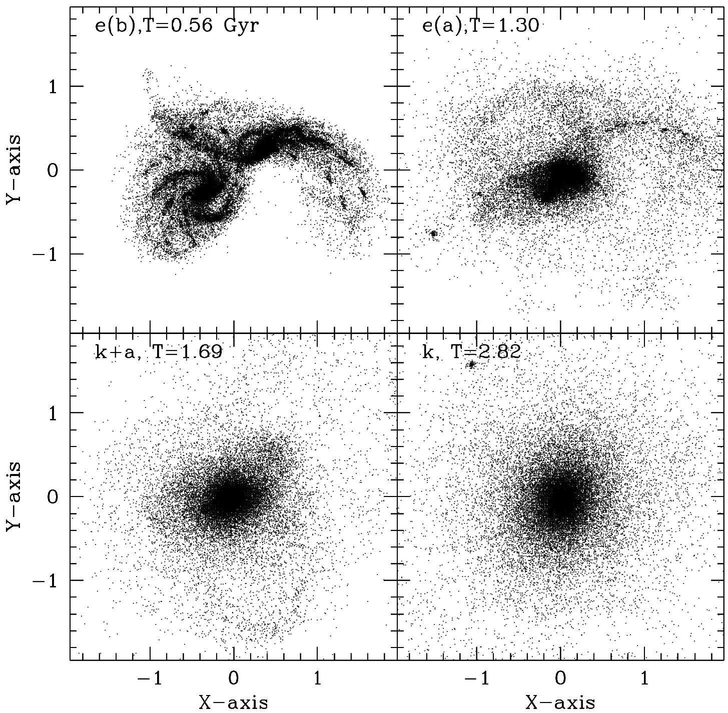
Fig. 4.— Time evolution of infrared luminosity ($L_{\rm IR}$) for the DS model (short-dashed), Hα luminosity for the DF one (dotted), and that for the DS one (solid) in units of W. Here $L_{\rm IR}$ represents the total luminosity from dust reemission of two merging disk galaxies.



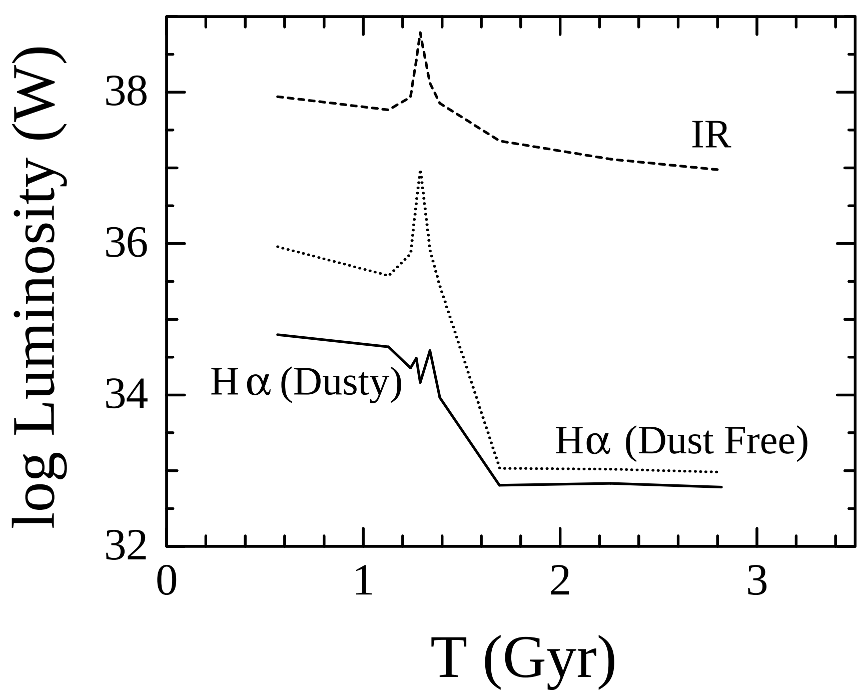
Core separation (kpc)
150
100
50
0
0
1
2
3
EW ([OII]) (Å)
400
300
200
100
0
Dusty SB
Dust free
EW(H δ) (Å)
0
−20
−40
T (Gyr)



EW ([OII]) (Å)
100
10
1
−40
−20
0
EW(H δ) (Å)
Dusty SB
Dust free
EW ([OII]) (Å)
100
10
1
−5
0
5
10
EW(H δ) (Å)
0.56 Gyr
2.8 Gyr
e(b)
e(c)
e(a)
k
k+a
a+k



e(b),T=0.56 Gyr
e(a),T=1.30
k+a, T=1.69
k, T=2.82
Y-axis
X-axis
-1
0
1



log Luminosity (W)
38
36
34
32
0
1
2
3
T (Gyr)
IR
Hα (Dusty)
Hα (Dust Free)