ARE RED TIDAL FEATURES UNEQUIVOCAL SIGNATURES OF MAJOR DRY MergERS?

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ABSTRACT

We use a cosmological numerical simulation to study the tidal features produced by a minor merger with an elliptical galaxy. We find that the simulated tidal features are quantitatively similar to the red tidal features, i.e., dry tidal features, recently found in deep images of elliptical galaxies at intermediate redshifts. The minor merger in our simulation does not trigger star formation due to active galactic nuclei heating. Therefore, both the tidal features and the host galaxy are red, i.e., a dry minor merger. The stellar mass of the infalling satellite galaxy is about $10^{10} M_\odot$, and the tidal debris reach the surface brightness of $\mu_B \sim 27$ mag arcsec$^{-2}$. Thus, we conclude that tidal debris from minor mergers can explain the observed dry tidal features in ellipticals at intermediate redshifts, although other mechanisms (such as major dry mergers) may also be important.

Subject headings: galaxies: kinematics and dynamics — galaxies: formation — galaxies: stellar content

1. INTRODUCTION

Recently van Dokkum (2005, hereafter vD05) analyzed unprecedentedly deep image of red galaxies at redshift around $z \sim 0.1$, and found that they often have diffuse tidal features over the scale of $\sim 50$ kpc. Furthermore, there is no associated star formation with these tidal features. vD05 call such features “dry tidal features”. vD05 also find that $\sim 30\%$ of the red galaxies in their sample are undergoing ongoing mergers, and the luminosity difference of these merging galaxies are often small (the ratio of the luminosities between the bigger and smaller galaxies is more than $0.3$). However, it is still an open question whether most dry tidal features are the remnants of such major dry mergers or whether other mechanisms can produce these features.

Here, we show that deep images of simulated red galaxies also display red tidal features. The galaxy studied is taken from a fully self-consistent $\Lambda$-dominated cold dark matter ($\Lambda$CDM) cosmological simulation. W e identify the responsible incident for the dry tidal feature, and find that the feature is due to the tidal tails created from an infall of a relatively small satellite galaxy, i.e., a minor merger. Our simulation suggests that such minor mergers may be responsible for some of the dry tidal features observed in vD05.

Our numerical simulations and the simulated elliptical galaxy are described in the next section. Section 2 presents a quantitative comparison between the dry tidal features in the simulated galaxy and those observed in vD05, and shows that the simulated features are consistent with the observed ones. The implications of this finding and our conclusions are given in the final section.

2. TARGET SIMULATED ELLIPITICAL GALAXY

The simulated images considered here are based on the elliptical galaxy model 2 presented in Kawata & Gibson (2005, hereafter KG05). KG05 carried out $\Lambda$CDM cosmological simulations using the galactic chemodynam- ics code, GCD+ (Kawata & Gibson 2003a). GCD+ is a three-dimensional N-body/smoothed particle hydrodynamics (SPH) code which incorporates self-gravity, hydrodynamics, radiative cooling, star formation, supernovae (SNe) feedback, and metal enrichment. GCD+ takes account of the chemical enrichment by both Type II (SNe II) and Type Ia (SNe Ia) SNe, mass-loss from intermediate mass stars, and follows the chemical enrichment history of both the stellar and gas components of the system.

The cosmological simulation adopts a $\Lambda$CDM cosmology ($\Omega_0=0.3$, $\Lambda_0=0.7$, $\Omega_b=0.019 h^{-2}$, $h=0.7$, and $\sigma_8=0.9$), and uses a multi-resolution technique to achieve high-resolution in the regions of interest, including the tidal forces from neighboring large-scale structures. The initial conditions for the simulations are constructed using the public software GRAFIC2 (Hertzsprung 2001). Gas dynamics and star formation are included only within the relevant high-resolution region ($\sim 12$ Mpc at $z=0$); the surrounding low-resolution region ($\sim 43$ Mpc) contributes to the high-resolution region only through gravity. Consequently, the initial condition consists of a total of $190093$ dark matter particles and $134336$ gas particles. The mass and softening lengths of individual gas (dark matter) particles in the high-resolution region are $5.86 \times 10^7$ ($3.95 \times 10^8$) $M_\odot$ and $2.27$ (4.29) kpc, respectively.

The elliptical galaxy found by KG05 (see also Kawata & Gibson 2003b) has a total virial mass of $2 \times 10^{11} M_\odot$. The galaxy is relatively isolated, with only a few low-mass satellites remaining at $z=0$. Figure 1 of Kawata & Gibson (2003b) shows the morphological evolution of dark matter in the simulation volume and the evolution of the stellar component of the target galaxy. The galaxy forms through conventional hierarchical clustering between redshifts $z=3$ and $z=1$. The morphology has not changed dramatically since $z=1$. 
KG05 introduced an active galactic nuclei (AGN) heating model in the simulation, and found that self-regulated activity of the AGN can suppress significant late-time star formation – characteristics not encountered in traditional dynamical models of ellipticals. As a result, their model (model 2 of KG05) succeeds in reproducing both the observed X-ray and optical properties of a massive elliptical galaxy.

In the chemodynamical simulation, the simulated star particles each carry their own age and metallicity “tag”, which enables us to generate an optical-to-near infrared spectral energy distribution for the simulated galaxy, when combined with our population synthesis code (which itself is based upon the population synthesis models of Kodama & Arimoto 1997). The population synthesis models are used to construct the photometric images used in our analysis.

3. DRY TIDAL FEATURES IN THE TARGET GALAXY

Figures 1-4 show the morphological evolution of the target galaxy over the redshift range $z = 0.4$ to $z = 0.22$ at two different projections: $x - y$ and $x - z$ projection in our three dimensional simulation coordinate system. The top and middle panels in each figure show the deep ($R < 27.0$ mag arcsec$^{-2}$) and shallow ($R < 24.5$ mag arcsec$^{-2}$) images, respectively. The deep images reveal some small tidal features which are not visible in the shallow images. The tidal features are similar to some of the diffuse tidal tail like features which are observed in vD05, e.g., 5-994, 9-360, 10-232, 16-650, 16-1302, 17-2819, 21-523, 25-3572 in his sample. For example, in Figure 1, the panels at $z = 0.37, 0.34$, and 0.32 show faint features like tidal tails. In fact, these are the tidal tails of a small satellite infalling into the target galaxy. The infalling satellite galaxy is highlighted by the circle in the top-left panel of Figures 1 and 2. The bottom panels show the distribution of the star particles. The grey dots show the whole particles, while the black dots represent the particles originated from the infalling satellite. The satellite particles are defined as the particles whose radius from the center of the satellite is less than 20 kpc at $z = 0.45$, well before the satellite falls into the target galaxy. The figures show that the tidal features seen in the deep R-band image correspond to the tidal tails of the infalling satellite. The tidal tails of the satellite start to be developed at $z = 0.40$. The satellite is tidally disrupted at $z = 0.37$, and the tidal features disappear around $z = 0.25$, which corresponds to about 1.3 Gyr. During the period when the tidal tails are visible in the bottom panels, the tidal features also appear in the deep image, although, not surprisingly, the strength of the features depends on the projection angle. vD05 claims that the tidal features appear smooth, showing little or no evidence for clumps and condensations. On the other hand, the simulated tidal features suggest the appearance of small clump prior to redshift $z = 0.34$, when the satellite has yet to fully disrupt. However, one can appreciate from Figure 11 of vD05 that some fraction of the observed galaxies present tidal tail-like features accompanied with small clumps, for example galaxies 9-360, 10-232, 17-2819, and 21-523. They may be an early stage of a minor merger. After redshift $z = 0.34$, there are appear to be no discernible condensations in the tidal tails.

Another important aspect reported in vD05 is that both the host galaxy and the tidal features are red, and there is no sign of star formation, i.e., they are “dry”. Similarly, in our simulation the produced features are in fact “dry tidal features”. Figure 5 shows the history of the star formation rate of the system, replotted from Figure 3 of KG05. Star formation stops in the target galaxy just before $z \sim 0.4$, due to the AGN heating (see KG05 for details). The AGN heating also suppresses star formation during the infall of the satellite galaxy.

Table 1 displays the luminosity, colors, and mass of the target galaxy and the infalling satellite at $z = 0.4$, i.e., before they start merging. Here, we adopt the diameter of $D = 5$ arcsec for a comparison with vD05. The stellar mass ratio between the satellite galaxy and the target galaxy is about 0.03, which indicates that the infalling satellite is small, i.e., a minor merger. This indicates that dry tidal features can result from minor mergers.

Table 1 gives two values for the luminosity of the target galaxy: One is the total luminosity, while the second value is the luminosity when the contribution from stars which are younger than 3 Gyr is ignored. Since star formation stops just before $z = 0.4$ in the target galaxy, the luminosity at $z = 0.4$ is affected by some young stars. As argued in KG05, this late cessation of star formation in the simulated galaxy is due to our simple modeling of the AGN heating. In this simulation, the AGN heating was started at $z = 1$, which is likely too late. If the AGN heating is added at a higher redshift, star formation is expected to stop earlier. For real elliptical galaxies, the epoch of the termination of star formation is expected to be rather random, and objects detected as red elliptical galaxies are likely at a stage well after star formation ceases (e.g., Shiya & Bekki 1998; van Dokkum & Franx 2001). Thus, the luminosity when the young stellar population is ignored is more appropriate for objects selected to be red and this is the luminosity we consider here. For such an object, the luminosity difference, $L_1/L_2 = 10^{(M_{R,1} - M_{R,2})/2.5}$, between the target galaxy and the satellite galaxy is 0.05, which is consistent with the lowest luminosity ratios found in the sample of ongoing mergers in vD05. In fact, those galaxies, 1-2874 and 5-2345 in vD05, show clear tidal tails, like those seen at $z = 0.37$ in Figure 1. Table 1 also shows the colors for both the target galaxy and the satellite, which indicates that they are both red, and the difference in $B - R$ is 0.14. This color difference is driven by the difference in metallicity.

Figure 6 shows the evolution of the luminosity and colors of the target galaxies. The filled circles indicate the colors and magnitudes before $z = 0.2$, when we found the dry tidal features. The open circles represent the evolution at later stages. The area enclosed by the dotted lines indicates the selection criteria in vD05. As discussed in vD05, their selection criteria preferably selects red galaxies at $z < 0.2$. The epoch we focus on here is a little earlier, and the target galaxy is redder than the selection criterion adopted by vD05. However, the epoch of minor mergers is random, and such minor mergers are expected to happen often in a ΛCDM cosmology. Hence, the results presented here indicate that if minor mergers happen at $z < 0.2$ for elliptical galaxies, the dry tidal features observed in vD05 can be produced.
Fig. 1.— Deep (upper panels) and shallow (middle panels) predicted $R$-band images of the target galaxy at the $x - y$ projections over the redshift range $z = 0.4$ to $z = 0.32$. Bottom panels represent the distributions of star particles (gray dots), the particles within the infalling satellite (see text for details) are highlighted by black dots. The infalling satellite galaxy is highlighted by the circle in the top-left panel. The prominent features are indicated by arrows. Numbers shown in the top panels are the tidal parameter, $t$, (see text) for each image.

Finally, we quantitatively confirm that the tidal features shown here are consistent with the features observed in vD05. To this end, we have analyzed the tidal parameter, $t$, which is defined in Section 5.3 in vD05, for all the $R$-band images presented in Figures 1-4. Here, we briefly explain our procedures to obtain the tidal parameter. We refer to the simulated galaxy $R$-band image as “$G$”. First, the galaxy images are fit by an elliptical model using the ellipse task in IRAF. The center position, ellipticity, and position angle are allowed to vary with radius. In cases where there are galaxies which overlap with the target galaxy in projection, the overlapping objects are also fit. The final model image is indicated by “$M$”. Finally, a fractional distortion image, “$F$”, is created by dividing $G$ by $M$. When the pixel value of $F$ is defined by $F(x, y)$, and the mean value of the image is $\bar{F}$, the tidal parameter $t$ which describes the level of distortion is defined as $t = \frac{F(x, y) - \bar{F}}{\bar{F}}$. Figure 7 demonstrates this procedure.

The values of $t$ are shown in all the top panels in Figures 1-4. We can see that the $R$-band images which have the tidal features show higher $t$ value ($t > 0.1$). During the epoch when the tidal features of the satellite galaxy are visible in the bottom panels ($z > 0.25$), $t$ appears to be higher. As expected, the $t$ values are lower after the tidal features disappear at $z \sim 0.25$. We also find that the value of $t$ depends on projection. In some cases, the different projections give vastly different $t$ values (compare for example the $x - y$ and $x - z$ panels at $z = 0.32$).

|          | the target galaxy | the satellite |
|----------|------------------|--------------|
| $M_R$ (mag) | $M_R$ (age $> 3$ Gyr) $^b$ | $B - R$ $^c$ | $M_*$ $(M_\odot)$ | $M_R$ (mag) | $B - R$ | $M_*$ $(M_\odot)$ |
| $-23.25$ | $-22.50$ | $2.53$ | $3.1 \times 10^{11}$ | $-19.17$ | $2.39$ | $1.0 \times 10^{11}$ |

$^a$The luminosity is measured within the projected diameter of 5 arcsec, i.e. 26.7 kpc at $z = 0.4$, while the mass is measured within the three dimensional diameter of 26.7 kpc.

$^b$The $R$-band luminosity, when the contribution from the stars younger than 3 Gyr is ignored.

$^c$The color, when the contribution from the stars younger than 3 Gyr is ignored.
Fig. 2.— Same as Figure 1 but for the $x - z$ projections. The high value of the tidal parameter at $z = 0.4$ is caused by poor model subtraction due to the small separation between the target galaxy and the infalling satellite.

Fig. 3.— Same as Figure 1 but for redshift range $z = 0.29$ to $z = 0.22$. The range of $t$ values is consistent with the weakly median value of $t$ is 0.13 in vD05) and strongly (median
4. DISCUSSION AND CONCLUSIONS

We have demonstrated that a minor merger of a satellite galaxy whose stellar mass is $10^{10} \, M_\odot$ with a massive elliptical galaxy can produce dry tidal features. In the present simulation, the features last about 1.3 Gyr, although the lifetime of such features must depend on the orbit of the satellite galaxy. Traditionally cosmological numerical simulations of elliptical galaxy formation have suffered from an inability to suppress late-time star formation in the simulation (e.g., Sugino & Ostriker 1998; Lewis et al. 2000).

Fig. 4.— Same as Figure 3 but for the $x-z$ projections.

Fig. 5.— Time-variation of the star formation rate for the target galaxy.

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Fig. 6.— Time variation of $B - R$ color and the $R$-band magnitude for the target galaxy. The numbers indicate redshift. The filled circles are the colors and magnitudes before $z = 0.2$, which we focus on in this paper. The open circles present the evolution after the stages which are discussed in this paper. The area enclosed by the dotted lines are the selection criteria in vD05.

Kay et al. 2003, Tornatore et al. 2003, Meza et al. 2003, Kawata & Gibson 2003b, Borgani et al. 2004, thereby being inconsistent with the observed red color in bright elliptical galaxies. However, self-regulated AGN heating, of the sort introduced in KG05 aids in the suppression of late-time star formation. As a result, both the host galaxy and tidal features in our simulation have the red colors consistent with those observed by vD05.

In a ΛCDM cosmology, minor mergers as seen in our simulations are expected to happen much more fre-
of Johnston et al. (2001), but with higher mass satellites, would be end-products of mergers with a system whose stellar mass is at least $\sim 10^{10} M_\odot$. Systematic studies like that of Johnston et al. (2001), but with higher mass satellites, would be useful for determining the mass range required to reproduce the observed dry tidal features.

The mechanism which creates the dry tidal feature in our simulation is similar to what is suggested for the formation of ripples (Schweizer 1984) and shells (Malin & Carter 1980) observed in nearby elliptical galaxies (e.g., Schweizer & Seitzer 1992; Colbert et al. 2001). Previous studies demonstrate that both a major (e.g., Hernquist & Spergel 1992) and minor (e.g., Quinn 1984; Dupraz & Combes 1986; Hernquist & Quinn 1988; Kojima & Noguchi 1997) merger can create shell features around giant elliptical galaxies. vD05 claims that their dry tidal features are different from the ripples and shells seen in nearby elliptical galaxies, because the dry tidal features look smoother than these other structures. However, vD05 also notes that the resolution of his images make it difficult to reach strong conclusions about the differences between these various types of features. According to the previous systematic studies of minor mergers (e.g., Hernquist & Quinn 1988), smoother features are produced if the infalling galaxy is more of a velocity dispersion supported system, i.e., elliptical galaxies. In addition, the tidal features are sensitive to the infalling galaxy within a radius of 100 kpc at z=1. As a result, we find little increase in stellar mass subsequent to redshift z=1 (Bell et al. 2004; Faber et al. 2005). It is an important question whether or not minor mergers, such as those described here, can similarly contribute to the increase in the mass of bright red galaxies. To check this, we compared the stellar mass of the simulated galaxy within a radius of 100 kpc at z=1 and z=0. As mentioned above, the simulated galaxy suffers from an excess of ongoing late-time star formation (prior to $z \sim 0.4$ – see also Fig. 9). Hence, we exclude stars whose age at the present epoch is less than 8 Gyrs. As a result, we find little increase in stellar mass subsequent to $z = 1$ (less than 5% growth). This is because the simulated galaxy does not undergo a major merger subsequent to redshift $z = 1.5$, and the disrupted satellites are much less massive than the host galaxy. (Note that in

![Figure 7](image-url)
Table 1. We measure the stellar mass within a small aperture and therefore underestimate the total stellar mass of the host galaxy. Therefore, minor mergers such as those described here are unlikely to contribute to the observed mass evolution of red galaxies. This means that major dry mergers must occur for a significant fraction of the red galaxy population, although we emphasise again that while potentially the dominant evolutionary pathway, it is not a mutually exclusive one. Interestingly, Kong et al. (2006) claim that the stellar mass increase is important for the relatively faint early-type galaxies (see also Renzini 2006). There may be a mass dependence of the dry major merger rate.

Our simulations of a single elliptical galaxy leaves many open questions. For example, how often do minor mergers happen for bright elliptical galaxies and how do the resulting features depend on the mass and morphology of the infalling galaxy. To address these questions, simulations of a large sample of ellipticals will be required.

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