HOW DRY ARE RED MERGERS?

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ABSTRACT

The focus of current research in galaxy evolution has increasingly turned to understanding the effect that mergers have on the evolution of systems on the red sequence. For those interactions purported to occur dissipationlessly (so-called dry mergers), it would appear that the role of gas is minimal. However, if these mergers are not completely dry, then even low levels of gas may be detectable. The purpose of our study is to test whether early-type galaxies with H i in or around them, or “wet” ellipticals, would have been selected as dry mergers by the criteria set forth in a 2005 study by van Dokkum. To that end, we examine a sample of 20 early types from the H i Rogues Gallery with neutral hydrogen in their immediate environs. Of these, the 15 brightest and reddest galaxies match the optical dry merger criteria, but in each case, the presence of H i (for the majority, at levels >10^8 M_☉), as well as significant star formation in some cases, means that they are not truly dry.

Key words: galaxies: evolution — galaxies: interactions — galaxies: ISM

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1. INTRODUCTION

The ways in which early-type galaxies form and evolve continue to be matters of much debate. Proposed mechanisms of formation have gone full circle, from monolithic collapse (e.g., Eggen et al. 1962), through late mergers of fully formed disk galaxies (e.g., Toomre & Toomre 1972; Kennicutt et al. 1998), to back to early formation of at least the stars (although perhaps not the assembly of the galaxies themselves; e.g., Bower et al. 1992; Ellis et al. 1997; van Dokkum et al. 1998). Certainly, observations suggest that at least some ellipticals were formed via mergers of gas-rich disks (e.g., Toomre & Toomre 1972; Schweizer 1982; Hibbard & van Gorkom 1996), although it is not obvious how common this formation history is. More recently, the debate has focused on the role of dissipationless merging between gas-poor galaxies (e.g., Ciotti et al. 2006; Scarlata et al. 2007). If mergers are indeed central to the process of early-type galaxy formation, then the nature of the progenitors and the characteristics of the encounter become essential in describing the evolution of these systems. The only clues available for discerning the evolutionary history of a galaxy are the nature of its composite populations. Using COMBO-17 survey data, Bell et al. (2004) found that the models which best fit the evolution of the mean color of 4690 red-sequence galaxies in the range 0.2 < z ≤ 1.1 (the vast majority of which are early types) are those of passively aging stellar populations. This is consistent with the majority of the galaxies’ stars (if not the galaxies themselves) being formed at redshifts >2. Recent studies, however, have also produced observations consistent with a dusting of more recent star formation in some ellipticals with otherwise ancient stars (e.g., Trager et al. 2000).

Studying the B-band luminosity density evolution with redshift of the above early-type galaxies over the range of 0.2 < z ≤ 1.1 reveals another clue about the histories of these systems; the stellar mass on the red sequence increases by a factor of 2–3 over this time (Bell et al. 2004). Such an increase in mass without significant star formation argues in favor of either very dusty or dissipationless mergers. Other questions have remained unanswered by the dissipational merger theory. For instance, it is surprising that mergers of spirals containing a range of stellar populations would produce the observed low scatter in the fundamental plane (e.g., Bower et al. 1998).

Arguments in favor of dissipationless mergers, on the other hand, include the observed signatures that these interactions involving disks leave behind in the form of fine structures. Shells and ripples are observed in a significant fraction of nearby ellipticals (Malin & Carter 1983; Schweizer et al. 1990), indicating the presence of a dynamically cold component, e.g., a disk (Hernquist & Quinn 1988), in the progenitors. In most disk galaxies, particularly later Hubble types, such disks are gas-rich (Roberts & Haynes 1994). Recently, van Dokkum (2005, hereafter VD05) studied the 126 brightest, reddest field galaxies in the NOAO Deep Wide Field Survey (NDWFS; Jannuzi & Dey 1999), and the Multiwavelength Survey by Yale-Chile (MUSYC; Gawiser et al. 2006). He found that of this sample, 71% of the 86 systems defined as E/S0 exhibit tidal features, such as tails or broad fans of stars, which are attributed to mergers or interactions. This is taken as evidence by VD05 for red or “dry” mergers, wherein red, bulge-dominated galaxies experience nearly dissipationless, or gasless, mergers in order to form massive ellipticals. Using only the ongoing mergers within this subsample, VD05 derived a mass accretion rate for galaxies on the red sequence of ΔM/M = 0.09 ± 0.04 Gyr⁻¹. From this rate, it can be inferred that in the range 0 < z < 1, the masses of bright red galaxies have undergone an increase in their stellar mass density by a factor of ≥2, provided this rate stays constant or increases with redshift, consistent with the COMBO-17 data presented in Bell et al. (2004). Thus, VD05 argues that dry mergers at low redshift are responsible for much of the local bright field elliptical galaxy population. However, no information regarding the gas content of these systems was presented.

Also from the NDWFS, Brown et al. (2007) compiled a sample of red galaxies to z = 1 that is an order of magnitude larger than similar surveys in the literature. These authors examine the B-band luminosity density evolution of red galaxies and also find that the stellar mass in these systems has increased by a factor of ~2;
We apply the \( k \) as \( S_0 \) by \( VD05 \); we apply the \( S_0 \) model to the 10 galaxies classified as red; 80\% of this sample; for the other galaxies, a median redshift of 0.1, and we know the precise redshifts for them; correction to both the \( B \) and \( R \) magnitudes and \( B - R \) colors to account for this change in redshift. The 126 galaxies of \( VD05 \) have a median redshift of 0.1, and we know the precise redshifts for \( \sim 80\% \) of this sample; for the other \( \sim 20\% \), we assume \( z = 0.1 \). We apply the \( k \)-corrections published in Poggianti (1997) using the \( E \) model in order to adjust the magnitudes and colors of the 86 galaxies classified as \( E/S0 \), as well as the 30 galaxies classified as \( S0 \) by \( VD05 \); we apply the \( S \) model to the 10 galaxies classified as \( S \) by \( VD05 \). The \( S \) model was not computed for \( R_C \) magnitudes in Poggianti (1997); for these systems, we used the values published for Johnson \( R \) magnitudes. The difference between the \( R \) and \( R_C \) \( k \)-corrections is less than 0.03 mag out to \( z = 0.24 \), which is accurate enough for our purposes.

At lower redshift, Schweizer et al. (1990) and Malin & Carter (1983) find that a significant fraction of nearby field ellipticals exhibit signs of fine structure such as shells, indicating the presence of a cold component. Among these samples, van Gorkom & Schiminovich (1997) find that 50\% of ellipticals in gas-rich environments have \( \text{H I} \) at the \( \sim 10^9 M_\odot \) level. So how "dry," exactly, are the mergers in the more complete sample of \( VD05 \)?

The purpose of our sample is to test whether early types with \( \text{H I} \) in or around them, or "wet" ellipticals, would have been selected as dry mergers by the criteria used in \( VD05 \). For this purpose it is useful to study systems listed in the \( \text{H I} \) Rogues Gallery (Hibbard et al. 2001), a collection of \( \text{H I} \) images of peculiar galaxies, as well as otherwise normal galaxies with peculiar \( \text{H I} \) morphology. Specifically, we consider those listed as being early types (Rogues classes pecEo, pecEi, and EpecH: peculiar ellipticals with \( \text{H I} \) outside or inside the optical body and normal ellipticals with peculiar \( \text{H I} \)), and we include two well-known merger remnants for comparison (NGC 3921 and NGC 7252). Our sample consists of galaxies from these classes with \( B \) and \( R \) magnitudes available in the literature that were measured inside appropriate aperture sizes. The \( \text{H I} \) data for each system were obtained at the VLA. The sample and each galaxy’s Rogues classification are listed in Table 1. The total number of galaxies in our sample is 20.

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2. THE SAMPLES

2.1. NDWFS and MUSYC

In \( VD05 \) the 126 reddest and brightest field galaxies in the NDWFS and the MUSYC around \( z = 0.1 \) were selected in order to uniformly study the morphologies of red galaxies between \( L^* \) and \( 3L^* \). The \( VD05 \) color selection criteria corresponds to \( 1.6 \leq (B - R) \leq 2.2, \text{ and } (B - R) > 1.6 + 0.12(R - 15) \), and the brightness criterion requires galaxies to have an apparent Cousins \( R \) magnitude \( > 17 \) (cf. Fig. 2 in \( VD05 \)). The galaxies were classified according to their optical morphology; approximately half of the sample exhibits low surface brightness features indicative of interactions, such as plumes and tails (\( VD05 \)). More dramatically, 70\% of the bulge-dominated early-type galaxies show such features; these bright, red, and morphologically selected systems are called red or "dry mergers" by \( VD05 \). The presence of tidal features was revealed by the deep imaging survey data, and each object was further classified as a "weak," "strong," or "ongoing" interaction. The color-magnitude diagram (CMD) of the \( VD05 \) sample is shown in Figure 1, with dotted lines highlighting the color and magnitude selection criteria.

To make the sample of \( VD05 \) consistent with ours for the purpose of comparison, we must adjust it to \( z = 0 \) and apply a \( k \)-correction to both the \( R \) magnitudes and \( B - R \) colors to account for this change in redshift. The 126 galaxies of \( VD05 \) have a median redshift of 0.1, and we know the precise redshifts for \( \sim 80\% \) of this sample; for the other \( \sim 20\% \), we assume \( z = 0.1 \). We apply the \( k \)-corrections published in Poggianti (1997) using the \( E \) model in order to adjust the magnitudes and colors of the 86 galaxies classified as \( E/S0 \), as well as the 30 galaxies classified as \( S0 \) by \( VD05 \); we apply the \( S \) model to the 10 galaxies classified as \( S \) by \( VD05 \). The \( S \) model was not computed for \( R_C \) magnitudes in Poggianti (1997); for these systems, we used the values published for Johnson \( R \) magnitudes. The difference between the \( R \) and \( R_C \) \( k \)-corrections is less than 0.03 mag out to \( z = 0.24 \), which is accurate enough for our purposes.

Taking these distances and \( k \)-corrections into account, the corresponding \( z = 0 \) CMD of the \( VD05 \) sample is shown beside its \( z = 0.1 \) counterpart in Figure 1, again with the \( z = 0.1 \) color and magnitude cutoffs displayed as dotted lines. The galaxies are no longer well constrained within an apparent magnitude-dependent parameter space; nine systems are actually fainter than the magnitude cutoff. For this reason we define a new magnitude limit of \( M_R = -20.5 \), and we also extend the magnitude-color criterion, \( (B - R) > 1.6 + 0.12(R - 15) \), to fainter magnitudes, as it still defines the "blue" edge of the sample well. These new criteria, which encompass all of the \( VD05 \) galaxies, are shown by the dashed lines in Figure 1 (right). Galaxies for which the redshift is unknown (and \( z = 0.1 \) is assumed) are represented by diamonds in Figure 1.

2.2. \( \text{H I} \) Rogues

The purpose of our sample is to test whether early types with \( \text{H I} \) in or around them, or "wet" ellipticals, would have been selected as dry mergers by the criteria used in \( VD05 \). For this purpose it is useful to study systems listed in the \( \text{H I} \) Rogues Gallery (Hibbard et al. 2001), a collection of \( \text{H I} \) images of peculiar galaxies, as well as otherwise normal galaxies with peculiar \( \text{H I} \) morphology. Specifically, we consider those listed as being early types (Rogues classes pecEo, pecEi, and EpecH: peculiar ellipticals with \( \text{H I} \) outside or inside the optical body and normal ellipticals with peculiar \( \text{H I} \)), and we include two well-known merger remnants for comparison (NGC 3921 and NGC 7252). Our sample consists of galaxies from these classes with \( B \) and \( R \) magnitudes available in the literature that were measured inside appropriate aperture sizes. The \( \text{H I} \) data for each system were obtained at the VLA. The sample and each galaxy’s Rogues classification are listed in Table 1. The total number of galaxies in our sample is 20.

2.3. Optical Photometry

For the 126 galaxies in the \( VD05 \) sample, apparent \( R \) magnitudes and \( B - R \) colors were measured inside an aperture of \( 5'' \)
We list a parameter listed in the NASA/IPAC Extragalactic Database (NED). We also calculate Hubble flow distances using Virgo-corrected velocities otherwise noted. For the galaxies not listed in Tully (1988), we are taken from the Nearby Galaxies Catalog (Tully 1988) unless Table 1 we list the adopted distances for each system; distances each galaxy as closely as possible in accordance with VD05. In order to directly compare the H\(_i\) sample in Figure 2, where we show the galaxies’ absolute

diameter. The central 5\(^{\prime}\) diameter area of a galaxy at \(z = 0.1\) corresponds to its central 9 kpc diameter area.

In order to directly compare the H\(_i\) Rogues selected above to VD05, absolute R magnitudes (\(M_R\)) and \(B - R\) colors are determined for each system from existing photometric data in the literature (see Table 1), using the HyperLeda database compilation of aperture photometry (Paturel et al. 2003). Taking into account the largest quoted uncertainty of these individual studies, the photometry of our sample is accurate to better than 0.1 mag.

The aperture sizes necessitated by each particular system in our sample differ, since the galaxies are all located at different distances; the aperture size is chosen to match the central 9 kpc of each galaxy as closely as possible in accordance with VD05. In Table 1 we list the adopted distances for each system; distances are taken from the Nearby Galaxies Catalog (Tully 1988) unless otherwise noted. For the galaxies not listed in Tully (1988), we calculate Hubble flow distances using Virgo-corrected velocities listed in the NASA/IPAC Extragalactic Database (NED). We also list a parameter \(R_{ap}\), defined as the ratio of the equivalent linear diameter of the adopted aperture (\(D_{ap}\)) to 9 kpc, or

\[
R_{ap} = \frac{D_{ap}}{9 \text{ kpc}},
\]

for each galaxy. When \(R_{ap} > 1.00\), our photometry is from a region larger than 9 kpc in diameter. For most of the sample, \(R_{ap}\) is within 10\% of 1.00; the four significant deviations are for NGC 7626 (\(R_{ap} = 0.87\)), IC 2006 and NGC 2865 (\(R_{ap} = 0.84\), and NGC 3921 (\(R_{ap} = 1.26\)). For the two most distant systems (\(d > 80\) Mpc), NGC 3921 and Mrk 315, we also apply magnitude and color k-corrections as described above.

We use the magnitude and color criteria specified in § 2.1 to identify galaxies from our Rogues sample that would have been selected by VD05. The Rogues sample is overplotted on the VD05 sample in Figure 2, where we show the galaxies’ absolute

| Object         | \(M_R\) | \(B - R\) | \(d\) (Mpc) | \(R_{ap}\) | Rogues Class. | Ref. |
|---------------|--------|----------|-------------|----------|----------------|-----|
| IC 2006       | -19.81| 1.44     | 15.7        | 0.84     | EpecH          | 1   |
| MCG - 5-7-1   | -20.27| 1.60     | 58.3*       | 0.98     | pecEi          | 2   |
| Mrk 315       | -22.11| 1.65     | 157         | 1.01     | pecEi          | 3   |
| NGC 474       | -20.92| 1.54     | 32.5        | 1.05     | pecEo          | 4*  |
| NGC 680       | -21.25| 1.68     | 37.7*       | 0.95     | pecEi          | *   |
| NGC 1052      | -21.27| 1.62     | 17.8        | 1.04     | EpecH          | 5   |
| NGC 1210      | -20.33| 1.25     | 48.7*       | 1.04     | pecEi          | 1   |
| NGC 1316      | -22.25| 1.55     | 16.9        | 0.97     | pecEo          | 6   |
| NGC 2768      | -21.69| 1.44     | 23.7        | 0.96     | EpecH          | 5   |
| NGC 2865      | -21.24| 1.43     | 35.7        | 0.84     | pecEi          | 7   |
| NGC 3921      | -21.77| 1.27     | 81.7*       | 1.26     | MR             | 8   |
| NGC 4125      | -21.19| 1.58     | 24.2        | 1.10     | pecEo          | 4   |
| NGC 4382      | -21.67| 1.45     | 16.8        | 0.90     | pecEo          | 9   |
| NGC 4406      | -21.60| 1.49     | 16.8        | 1.09     | pecEo          | 4   |
| NGC 5018      | -22.12| 1.53     | 40.9        | 0.96     | pecEo          | 7   |
| NGC 5128      | -21.07| 1.65     | 3.8**       | 1.12     | pecEi          | 1   |
| NGC 5903      | -21.26| 1.71     | 35.9        | 1.05     | EpecH          | 6   |
| NGC 7135      | -20.75| 1.64     | 34.7        | 1.11     | pecEo          | 4   |
| NGC 7252      | -21.78| 1.31     | 62.9*       | 1.01     | MR             | 4   |
| NGC 7626      | -21.42| 1.72     | 46.0*       | 0.87     | pecEo          | 10  |

Notes.—Columns display the object name, \(M_R\) in the Cousins system, \(B - R\) distance (Mpc), aperture fraction (defined in the text), H\(_i\) classification in the Rogues Gallery (Hibbard et al. 2001), and references to the photometry. Distances are taken from Tully (1988), except for those marked with an asterisk, which are calculated using Virgo-corrected velocities from NED and assuming \(H_0 = 75\) km s\(^{-1}\) Mpc\(^{-1}\) in order to be consistent with Tully (1988). The distance to NGC 5128 is taken from Rejkuba et al. (2005) and is marked with two asterisks. Photometry from references 4, 6, 8, and 10 has been converted to Cousins. The photometry for NGC 474 is marked as suspect by Sandage & Visvanathan (1978), and the unpublished photometry for NGC 680 is available through the HyperLeda aperture photometry database (a description of this specific database is available in Prugniel & Heraudeau 1998). A Rogues classification of pecEo refers to peculiar ellipticals with H\(_i\) outside of the optical body; pecEi refers to peculiar ellipticals with H\(_i\) inside of the optical body. EpecH refers to normal early-type galaxies with peculiar H\(_i\), and MR refers to merger remnants.

References.—(1) Lauberts & Valentijn 1989; (2) Lauberts 1984; (3) Moles et al. 1987; (4) Sandage & Visvanathan 1978; (5) Peletier et al. 1990; (6) Sandage 1975; (7) Poulain & Nieto 1994; (8) Huchra 1977; (9) Schroder & Visvanathan 1996; (10) Sandage 1973.
magnitudes as a function of $B - R$ color. The VD05 $z = 0.1$ color and apparent-magnitude-dependent selection criteria are shown as in Figure 1, and the color-magnitude extension, as well as the fainter magnitude cutoff we use, are also displayed. Although the H$\textsc{i}$ sample is fainter overall than the sample of VD05, the overlap between the samples is obvious.

3. RESULTS AND DISCUSSION

3.1. "Wet" Red Rogues

As is evident in Figure 2, 15 members (75\%) of the H$\textsc{i}$ Rogues sample would have been selected by the VD05 color criteria for dry mergers. These 15 “wet” Red Rogues (with neutral hydrogen in or around them) are displayed in Figure 3, with H$\textsc{i}$ contours superimposed; the three normal ellipticals with peculiar H$\textsc{i}$ are shown first, followed by the 12 peculiar ellipticals with H$\textsc{i}$. The presence of H$\textsc{i}$ in these systems varies from lying in a well-defined disk and shells in Cen A (NGC 5128) to being confined in a gas-rich companion for NGC 4382.

The optical morphologies of these Red Rogues appear very similar to the sample studied in VD05. Twelve of the 15 Red Rogues are classified in the Rogues Gallery as pecEo and pecEi, as they exhibit signs of tidal interaction at low surface brightness levels in the form of tails and plumes of stars; the other three Red Rogues, as published in the Rogues Gallery, with H$\textsc{i}$ contours overlaid on optical DSS images. Row 1: NGC 2768 (Schiminovich et al. 2001), NGC 5903 (Appleton et al. 1990), NGC 1052 (van Gorkom et al. 1986), and NGC 5128 (Schiminovich et al. 1994). Row 2: NGC 680 (van Moorsel 1988), NGC 1316 (Horellou et al. 2001), and NGC 7626 (Hibbard & Sansom 2001). Row 3: NGC 4125 (Rupen et al. 2001), NGC 4382 (Hibbard & Sansom 2001), NGC 4406 (Li & van Gorkom 2001), and NGC 5018 (Kim et al. 1988). Row 4: Mrk 315 (Simkin & MacKenty 2001), NGC 474 (Schiminovich et al. 2001), NGC 2865 (Schiminovich et al. 1995), and NGC 7135 (Schiminovich et al. 2001). [See the electronic edition of the Journal for a color version of this figure.]
Rogues are EpecH, or normal ellipticals from the optical standpoint. This matches the behavior of VD05’s bulge-dominated population, 71% of which (the dry mergers) show tidal features, with the remainder exhibiting no clear sign of an interaction history down to very low surface brightness levels, making our “wet” peculiar and “wet” normal populations a counterpart to the red peculiar and red normal populations of VD05. A comparison of the deep co-added BVR optical imaging of cdfs-1100 from the MUSYC survey, used in VD05, to a DSS image of NGC 7135 (one of the Red Rogues) is shown in Figure 4; the galaxies in these two samples are clearly morphologically similar.

That 15 out of 20 Rogues would have been selected by the VD05 dry-merger color criteria is in itself an interesting result, considering that the Rogues are a sample selected to have gas. However, perhaps even more interesting is the ability to look for trends within the sample. In Figure 5 normal ellipticals and peculiar ellipticals are plotted using different symbols; no clear trend is apparent. This is possibly due to either our small sample size or the fact that if we were to obtain deeper optical imaging (such as that used by VD05), it is possible that we would detect tidal features in our “normal” early-type systems. The two merger remnants (MRs), NGC 3921 and NGC 7252, are indicated by asterisks in the figure; they are clearly too blue to be selected by the VD05 criteria. In VD05, 18% of the red objects are currently undergoing interactions, but our sample was chosen on the basis of looking almost exclusively at galaxies classified as ellipticals or peculiar ellipticals; we added two well-known merger remnants for comparison, but clearly ongoing mergers are listed under other Rogues classes. We therefore selected against “ongoing merger” systems in favor of systems which have likely already finished merging (i.e., the pecEo and pecEi galaxies, as well as the MRs).

VD05 uses a subsample of merger pairs and merger remnants in order to estimate the effects that dry mergers would have on the evolution of the luminosity function of red galaxies. He finds that, with some caveats, dry mergers can explain the constant luminosity density out to $\sigma = 1$, which is incompatible with only passive evolution of red galaxies. We, however, find that if the “wet” peculiar Red Rogues presented in this paper are actually the local analogs of these higher redshift merger remnants, then the VD05 systems are not necessarily dissipationless.

### 3.2. Star Formation

It is interesting to note that one of the systems which falls unambiguously within the VD05 sample in Figure 2 is Mrk 315, which has a star formation rate of $30-40 M_\odot$ yr$^{-1}$ (Ciroi et al. 2005). The presence of $H_\alpha$ coupled with such a high rate of star formation makes this galaxy seem hardly dry. At least one other Red Rogue is also forming stars. Centaurus A (NGC 5128) has $1.5 \times 10^7 M_\odot$ of $H_\alpha$ associated with its shells and $4.5 \times 10^6 M_\odot$ in the disk (Schiminovich et al. 1994), where vigorous star formation is occurring (Ebneter & Balick 1983). CO has also been observed in the disk (at the level of $2 \times 10^6 M_\odot$; Eckart et al. 1990), as well as in the shells, where it corresponds to $4.3 \times 10^7 M_\odot$ of $H_2$ (Charmandaris et al. 2000). Although Cen A has the appearance of simply an elliptical galaxy with a dust lane, it actually possesses a disk which is energetically forming stars despite its “red” classification. The presence of gas does not necessarily imply star formation in the other Red Rogues, but in the cases of Mrk 315 and Cen A it does.

In light of our findings, it is worth considering whether the evolutionary histories derived by VD05 are strongly constrained by the broadband filters available to him ($BVRI$). The inclusion of shorter and/or longer wavelength data (UV, $U$-band, NIR) or spectroscopy would better constrain these histories, especially by breaking the degeneracy between extinction and stellar ages (e.g., Gil de Paz & Madore 2002; Anders et al. 2004) or by detecting “frostings” of younger stars (Trager et al. 2001). If they revealed a component of young stars, these better-constrained star formation histories would then also constrain how dry a previous merger could have been.

### 4. Conclusion

In this paper we have examined the selection criteria for picking out dry mergers as used in VD05 by comparing his sample to one consisting of early types with known $H_\alpha$ properties. For our small sample of 20 systems, we find that 15 galaxies with $H_\alpha$ (or 75%) would have been selected by the VD05 dry-merger criteria.
VD05 invoked dry merging to explain the evolution of the luminosity function of bright red galaxies since $z = 1$. However, we show that selecting dry mergers on the basis of their colors is not sufficient to ensure that the systems will not have gas. The presence of H i, in turn, allows for the possibility of significant star formation, and our sample contains at least two examples for which this is the case.

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