THE DEEP2 GALAXY REDSHIFT SURVEY: EVOLUTION OF CLOSE GALAXY PAIRS AND MAJOR-MERGER RATES UP TO z ~ 1.2

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ABSTRACT

We derive the close, kinematic pair fraction and merger rate up to redshift z ~ 1.2 from the initial data of the DEEP2 Redshift Survey. Assuming a mild luminosity evolution, the number of companions per luminous galaxy is found to evolve as (1 + z)^m, with m = 0.51 ± 0.28; assuming no evolution, m = 1.60 ± 0.29. Our results imply that only 9% of present-day L* galaxies have undergone major mergers since z ~ 1.2 and that the average major merger rate is about 4 × 10^{-4} h^3 Mpc^{-3} Gyr^{-1} for z ~ 0.5−1.2. Most previous studies have yielded higher values.

Subject headings: galaxies: evolution — galaxies: interactions — large-scale structure of universe

1. INTRODUCTION

Galaxy interactions and mergers are an integral part of our current paradigm of the hierarchical formation and evolution of galaxies. Such processes are expected to affect the morphologies, gas distributions, and stellar populations of galaxies (e.g., Mihos & Hernquist 1994, 1996; Dubinski et al. 1996). Although mergers are rare today (Patton et al. 2000, hereafter P2000), cold dark matter N-body simulations show merger rates of halos increasing with redshift as (1 + z)^m, with 2.5 ≤ m ≤ 3.5 (Governato et al. 1999; Gottlöber et al. 2001).

Observations, however, have yielded results with 0 ≤ m ≤ 4 (Zepf & Koo 1989; Burkey et al. 1994; Carlberg et al. 1994; Woods et al. 1995; Yee & Ellingson 1995; Patton et al. 1997; Neuschaefer et al. 1997; Le Fèvre et al. 2000; Carlberg et al. 2000; Patton et al. 2002; Bundy et al. 2004). The diverse results are likely due to different pair criteria, observational techniques, selection effects, and cosmic variance (Abraham 1999; P2000). To identify close pairs, the most secure method is via spectroscopic redshifts for both galaxies to find kinematic pairs (Patton et al. 2002, hereafter P2002). This Letter adopts the approach of P2002 and uses the early data of the DEEP2 (Deep Extragalactic Evolutionary Probe 2) Redshift Survey (Davis et al. 2003; S. M. Faber et al. 2004, in preparation) to derive the pair fraction and merger rates up to z ~ 1.2. In § 2, we describe the sample and selection functions. In § 3, we use both the projected separation and the relative velocity to select close galaxy pairs and to determine their evolution. Major merger rates out to z ~ 1.2 are computed in § 4. The results are discussed in § 5. Throughout this Letter, we adopt a cosmology of H_0 = 70 km s^{-1} Mpc^{-1}, Ω_m = 0.3, and Ω_Λ = 0.7.

2. DATA AND SELECTION FUNCTIONS

The DEEP2 Redshift Survey (DEEP2 for short) will measure redshifts for ~50,000 galaxies at z ~ 1 (Davis et al. 2003) using DEIMOS (Deep Imaging Multi-Object Spectrograph; Faber et al. 2003) on the 10 m Keck II telescope. The survey covers four fields, with Field 1 (Extended Groth Strip) being a strip of 0.25 × 2 deg^2 and Fields 2, 3, and 4 each being 0.5 × 2 deg^2. The photometry is based on BRI images taken with the 12k × 8k camera on the Canada-France-Hawaii Telescope (see Coil et al. 2004 for details). Galaxies are selected for spectroscopy using a limit of R_AB = 24.1 mag. Except in Field 1, a two-color cut is also applied to exclude galaxies with redshifts z < 0.75. A 1200 line mm^{-1} grating (R = 5000) is used with a spectral range of 6400–9000 Å, where the [O ii] λ3727 doublet would be visible at z ~ 0.7–1.4. The data are reduced using an IDL pipeline developed at UC-Berkeley (J. A. Newman et al. 2004, in preparation). The K-correction is derived from spectra of local galaxies (C. N. A. Willmer et al. 2004, in preparation). The data used here are from Fields 1 and 4, cover ~0.4 deg^2, and contain ~5000 galaxies.

To measure the spectroscopic selection functions (see L. Lin et al. 2004, in preparation, for details), we compared the sample with successful redshifts to galaxies in the full photometric catalog that satisfy the limiting magnitude and two-color cuts. Following analogous approaches by Yee et al. (1996) and P2002, we calculate the spectroscopic weight of each galaxy as 1/S, where S is the spectroscopic selection function derived from the R magnitude, B − R and B − I colors, R-band surface brightness μ_r, and local galaxy density of the galaxy itself. To correct for bias due to slit collisions (Davis et al. 2004), we also compute the angular weight, w(θ), as a function of angular separation θ (P2002). For θ ≤ 20", we find 0.95 ≤ w(θ) ≤ 1.5, a result confirmed with the DEEP2 mock catalog of Yan et al. (2004).
A major limitation on the direct measurement of merger fractions for galaxies is the difficulty in identifying ongoing mergers, especially for distant galaxies. One alternative is to count only the pairs with projected separations $\Delta r$ and relative line-of-sight heliocentric velocities $\Delta v$ less than $r_{\text{max}}$ and $v_{\text{max}}$, respectively. A large fraction of pairs with physical separations less than 20 h$^{-1}$ kpc and velocity differences less than 500 km s$^{-1}$ appear to have disturbed morphologies or signs of interactions, and these galaxies are expected to merge within 0.5 Gyr (P2000). In our work, close pairs are defined such that their projected separations satisfy $10 h^{-1}$ kpc $\leq \Delta r \leq r_{\text{max}}$ and their rest-frame relative velocities $\Delta v$ are less than 500 km s$^{-1}$. We adopt an inner cutoff with a projected distance $10 h^{-1}$ kpc so as to avoid the ambiguity between very close pairs and single galaxies with multiple star-forming knots. We choose values of $r_{\text{max}} = 30, 50,$ and $100 h^{-1}$ kpc, where $30 h^{-1}$ kpc is most likely to include genuine merger pairs, while the two larger separations provide larger samples and thus better statistics. To ensure the selection of the same types of galaxies at different redshifts in the presence of luminosity evolution, P2002 adopted a specific range in evolution-corrected absolute magnitude $M_{r}^c$, defined as $M_{r}^c + Q(z)$, where the evolution is parameterized as $M(z) = M(z = 0) - Q(z)$. Following P2002, we adopt $Q = 1$ as a primary model, and we also study the effect of different models on the pair statistics. We restrict the analysis to galaxies with luminosities $-21 \leq M_{r}^c \leq -19$ for $z = 0.45$–1.2. Since there is only a 2 mag range in our sample, and assuming a constant $M/L$ ratio, most observed pairs are thus major mergers, i.e., mass ratios between 1 : 1 and 6 : 1. Using data from the DEEP2 Fields 1 and 4 helps us to reduce the effects of cosmic variance. Following P2000 and P2002, we compute the average number of companions per galaxy

$$N_c = \frac{\sum_{i=1}^{N_{\text{tot}}} \sum_{j=1}^{N_{ij}} w_i w_j (\theta_i)}{N_{\text{tot}}^{\text{max}}}$$

where $N_{\text{tot}}$ is the total number of galaxies within the chosen magnitude range, $w_i$ is the spectroscopic weight for the $i$th companion belonging to the $j$th galaxy, and $(\theta_i)$ is the angular weight for each pair as described in § 2. Details of the weighting scheme can be found in § 5 of P2002 and references therein. This quantity $N_c$ is similar to the pair fraction when there are few triplets or higher order $N$-tuples in the sample, which is the case here. In this work, $N_c$ will sometimes simply be referred to as the pair fraction.

Figure 1 shows $N_c$ versus redshift $z$ for a sample with $r_{\text{max}} = 500$ km s$^{-1}$ and $10 h^{-1}$ kpc $\leq \Delta r \leq r_{\text{max}}$ with $r_{\text{max}} = 30, 50,$ and $100 h^{-1}$ kpc, respectively. In the case of using $r_{\text{max}} = 50 h^{-1}$ kpc, we find 79 paired galaxies out of 2547 galaxies. The derived $N_c$ is $\approx$8% at $z \approx 0.6$ and increases to 10% at $z \approx 1.1$. Figure 1 also shows results from the SSRS2 (Southern Sky Redshift Survey; P2000) at $z \approx 0.015$ and CNOC2 (Canadian Network for Observational Cosmology; P2002) at $z \approx 0.3$, after corrections that adopt the same cosmology and the same luminosity range.

The DEEP2 sample is $R$-band–selected and hence, for redshifts greater than 0.8, is biased toward galaxies that are bright in the rest-frame UV, i.e., against faint red galaxies, especially at redshifts $z > 1.0$. To avoid this bias, we divide our sample into blue and red galaxies using the color bimodality feature and then repeat the calculation of $N_c$ using $r_{\text{max}} = 50 h^{-1}$ kpc for blue galaxies at $z = 0.3$ (CNOC2), 0.6, and 0.85 bins (DEEP2). When using only blue galaxies, the values of the pair fraction $N_c^{\text{blue}}$ decrease at $z = 0.3$ and 0.85 but increase at $z = 0.6$ compared to the results using the original sample. The changes in the measured value of $N_c$ could be up to a factor of 2, depending on the field and redshift. To mitigate the underestimation of the pair fraction in the redshift bin $1.0 < z < 1.2$, we calculate a corrected $N_c$, at $z = 1.1$ as

$$N_c^{\text{cov}} = \max \left[ N_c, 2 N_c^{\text{blue}} \right].$$

shown as open triangles in Figure 1. Parameterizing the evolution of $N_c$ as $N_c(0)(1 + z)^\alpha$, we find that the best fit of $(N_c(0), m)$ is $(0.029 \pm 0.005, 1.08 \pm 0.40)$ with $\chi^2 = 0.27$ for $r_{\text{max}} = 30 h^{-1}$ kpc, $(0.068 \pm 0.008, 0.51 \pm 0.28)$ with $\chi^2 = 0.89$ for $r_{\text{max}} = 50 h^{-1}$ kpc, and $(0.177 \pm 0.014, 0.47 \pm 0.18)$ with $\chi^2 = 1.2$ for $r_{\text{max}} = 100 h^{-1}$ kpc. For the highest redshift bin, $N_c^{\text{cov}}$ instead of $N_c$ is used for the above fitting procedure. The best fits are shown as long-dashed curves in Figure 1. For three different choices of $r_{\text{max}}$, we find only a small increase of $N_c$ from redshifts $z = 0$ to $z = 1.2$. In Figure 1, we also list the upper limits of errors from the cosmic variance for each redshift bin calculated by assuming a spherical geometry of the survey volume. Incorporating the cosmic variance into the fitting procedure slightly raises $m$ to 0.62 $\pm$ 0.49 for $r_{\text{max}} = 50 h^{-1}$ kpc.

The adopted choice of $Q = 1$ in the luminosity evolution model sets the luminosity range of the sample at each redshift and thus affects our results. To assess this effect, we repeat the pair analysis for other choices of $Q$. The luminosity ranges are chosen such that they are locked to $-22 \leq M_{r}^c \leq -20$ at $z = 1.0$. Using $r_{\text{max}} = 50 h^{-1}$ kpc and an upper redshift limit of $z = 1$, we find that $m$ varies from $1.60 \pm 0.29$ for $Q = 0$, $0.86 \pm 0.29$ for $Q = 0.5$, $0.41 \pm 0.30$ for $Q = 1$, to
choices of separation limits.

\[ Q = 2 \]

In Figure 2, we plot \( N_c \) as a function of absolute \( B \)-band magnitude \((M_B)\) for three redshift samples. A clear dependence of \( N_c \) on \( M_B \) is evident. The trend that \( m \) decreases with \( Q \) can be understood as the result of including fainter galaxies and thus having larger \( N_c \) at lower redshifts when adopting higher \( Q \)-values. Nevertheless, even with the lowest choice of \( Q = 0 \) to maximize \( m \), models with \( m > 3.5 \) are ruled out at a 3 \( \sigma \) level of confidence for all three choices of separation limits.

4. MAJOR MERGER RATES

The comoving merger rate, usually defined as the number of mergers per unit time per comoving volume, can be estimated as

\[ N_{\text{mg}} = 0.5n(z)N_c(z)C_{\text{mg}}T_{\text{mg}}^{-1}, \]  

(3)

where \( T_{\text{mg}} \) is the timescale for physically associated pairs to merge, \( C_{\text{mg}} \) denotes the fraction of galaxies in close pairs that will merge in \( T_{\text{mg}} \), and \( n(z) \) is the comoving number density of galaxies. The factor 0.5 is to convert the number of galaxies into the number of merger events. The merger rate calculated above, however, is not suitable for comparison to the merger rate derived from morphological approaches. The reason is that while we have restricted the luminosity range of companions to compute \( N_c \), the morphological approach does not. To correct for this restriction, equation (3) can be modified:

\[ N_{\text{mg}} = (0.5 + G)n(z)N_c(z)C_{\text{mg}}T_{\text{mg}}^{-1}, \]  

(4)

where the added parameter \( G \) accounts for the excess number of companions failing to fall into our sample. Assuming that the maximum mass ratio needed to yield significant morphology distortions is 4 : 1, we calculate the value of \( G \) as 1.24 for \(-21 \leq M_B \leq -19\) using the local luminosity function (Driver & De Propris 2003). \( T_{\text{mg}} \) depends on the relative mass ratio, dynamical orbit, and detailed structure of the two merging galaxies, and thus it varies from case to case. Here we adopt \( T_{\text{mg}} = 0.5 \) Gyr, a value suggested by N-body simulations and simplified models (Mihos 1995; P2000). The value \( C_{\text{mg}} \) is approximately 0.5 for close pairs with \( 5 \) h\(^{-1}\) kpc \( \leq \Delta r \leq 20 \) h\(^{-1}\) kpc and \( v_{\text{max}} = 500 \) km s\(^{-1}\); this estimate is based on morphological studies of local close pairs (P2000). Nevertheless, both \( T_{\text{mg}} \) and \( C_{\text{mg}} \) remain uncertain.

The derived merger rates are displayed in Figure 3. Here we have applied the pair fraction evolution of \( m = 0.51 \) derived for the \( r_{\text{max}} = 50 \) h\(^{-1}\) kpc case to the \( z = 0 \) (SSRS2) \( N_c \) result for pairs with \( 5 \) h\(^{-1}\) kpc \( \leq \Delta r \leq 20 \) h\(^{-1}\) kpc. The parameter \( n(z) \) is calculated as the sum of the number of galaxies in the adopted magnitude range, each weighted by its spectroscopic weight and divided by the comoving volume occupied by the included sources. The errors shown for DEEP2 measurements represent 40\% variations that are typical for close pair counts in our sample, and they do not include the uncertainties of \( T_{\text{mg}} \) and \( C_{\text{mg}} \). Also shown are the results from Conselice et al. (2003), who relied on morphologically identified mergers for \( M_B < -19 \) using Hubble Space Telescope (HST) data in the Hubble Deep Field–North (filled triangles). Clearly, the comoving merger rate in our data changes little with redshift. From \( z \approx 0.5 \) to \( z \approx 1.2 \), the average is \( N_{\text{mg}} \approx 4 \times 10^{-4} \) h\(^{-1}\) Mpc\(^{-3}\) Gyr\(^{-1}\) for \(-21 \leq M_B \leq -19\). This value is about 1 order of magnitude lower than the average merger rate for galaxies with \( M_B \leq -19 \) derived by Conselice et al. (2003).

Finally, we calculate the merger remnant fraction, \( f_{\text{con}} \), defined as the fraction of present-day galaxies that have undergone major mergers (P2000). Adopting the merger fraction \( C_{\text{mg}} \) to be 0.5 and \( T_{\text{mg}} \) to be 0.5 Gyr, we estimate, using equation (32) in P2000, that about 9\% of present \( L^* \) luminous galaxies have undergone major mergers since \( z \approx 1.2 \).

5. DISCUSSION

Studies up to \( z \approx 1 \) using pair counts have found a wide range in the evolution of merger rates. For example, based on roughly 300 Canada-France Redshift Survey galaxies measured with HST, Le Fèvre et al. (2000) concluded that the pair fraction evolves with \( m = 2.7 \pm 0.6 \) while the fraction of merger candidates evolves with \( m = 3.4 \pm 0.6 \). In contrast, Carlberg et al. (2000) measured the mean fractional pair luminosity from \( z = 0.2 \) to 1 and found no evolution with \( m \approx 0 \pm 1.4 \), consistent with our result. Since the pair fraction depends on adopted luminosity limits, differences among studies may de-
pend on the choice of luminosity evolution models. Le Fèvre et al. (2000), e.g., applied no corrections, while Carlberg et al. (2000) adopted the $Q = 1$ model, as we do here. The key advantages of our pair sample over previous surveys include having measurements at $z > 1$, a larger sample, and more restrictive pair criteria than those adopted by Le Fèvre et al. (2000) and Carlberg et al. (2000).

The discrepancy in the derived merger rates at $z \sim 1$ between our estimates and those from Conselice et al. (2003) is more difficult to reconcile. Besides the choice of luminosity ranges and the uncertainties in $C_{mg}$ and $T_{mg}$, other factors may explain the discrepancy. First, cosmic variance can always come into play, since most morphological studies have been forced to use the few small fields covered deeply by HST imaging, whereas pair-count surveys cover much larger areas. Second, the two approaches may sample interacting and merging galaxies at different stages, with morphological approaches identifying very advanced mergers and merger remnants, while the pairs detect some of the same systems before distortions are discernible. Matching the derived merger rates from these two approaches requires knowledge of the precise timescales of close pairs and of the duration time for the appearance of distorted morphologies. However, neither is well understood yet. Third, while our close pairs identify only major mergers, morphological criteria may be sensitive to minor mergers as well. Finally, both the pair-count and morphology methods are subject to systematic uncertainties that require detailed modeling (Bell 2004). Given the current discrepancy in results, it behooves us to study the connection between kinematic pairs and morphologically disturbed galaxies at various redshifts, both via observational approaches (P2000; J. Lotz et al. 2004, in preparation) and through numerical simulations (T. J. Cox et al. 2004, in preparation).

The merger rates from pair counts are also an excellent test for those estimated from $N$-body simulations, since the former reveal the behavior of luminous baryons while the latter reflect the behavior of dark halos. Gottlöber et al. (2001) defined merger rates in $N$-body simulations as equivalent to the major merger fraction per gigayear by tracing the formation and evolutionary history of each halo. These fractions will differ from the pair fractions roughly by a constant, and therefore their redshift evolution is amenable to direct comparisons. They found merger rates evolving as $(1+z)^{3}$ up to $z \sim 2$. This theoretical value of $m = 3$ is significantly higher than the $m \approx 0.5$ we find from observed pair counts. We should, however, be wary about this comparison for the following reasons. First, definitions of merger rates in observations and simulations may not be consistent with each other, since the halos and visible galaxies span different size scales and since $N$-body simulations also suffer limitations in resolution. Second, the merger rates/fractions of halos are likely to be a function of halo mass, which is suggested by our finding that the galaxy pair fraction is a function of luminosity. Pair-count works using $K$-band-selected samples (e.g., Bundy et al. 2004) can also provide another avenue for testing the mass dependence of merger rates, since the $K$-band luminosity is more representative of any underlying stellar mass and suffers less from evolution corrections. Although preliminary, mock catalog simulations by E. Van Kampen et al. (2004, in preparation) predict flat slopes for the pair-count fractions (see Fig. 3 of Bell 2004), just as seen in our observations. We expect a dramatic improvement in our understanding of merger histories via pair counts after more realistic comparisons to simulations are possible and especially after a 10-fold increase in sample size when DEEP2 is complete in 2005.

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