A SURVEY OF FAINT GALAXY PAIRS

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ABSTRACT

A sample of faint, $V$ magnitude selected, galaxy pairs, having physical separations less than approximately $20h^{-1}$ kpc, is used to examine the rise in the merger rate with redshift and the statistical relations between close pairs and the field galaxy population. Redshifts have been obtained for 14 galaxies ($V \leq 22.5$) that are in close ($\theta < 6''$) pairs, along with a comparison sample of 38 field galaxies. Two color photometry is available for about 1000 galaxies in the same fields. The average redshift of the $V \leq 22.5$ field population is 0.36, statistically equal to the average redshift of 0.42 for the pairs. The similarity of the two redshift distributions, $\Delta z \leq 0.1$, limits any differential luminosity enhancement of close pairs to less than half a magnitude. The pairs are somewhat bluer than the field and have nearly twice the average [O II] detection rate of the field, but the differences are not statistically significant. The field population has an angular correlation at separations of $\theta \leq 6''$ higher than the inward extrapolation of $\omega(\theta) \propto \theta^{-0.8}$, which may be a population of “companions” not present at the current epoch, or, luminosity enhancement of intrinsically faint galaxies in pairs. Physical pairs comprise about 7% of the faint galaxies in our survey fields. The same physical separation applied to local galaxies finds only 2.6% in pairs. If the rise in close low relatively velocity pairs with redshift is parameterized as $(1 + z)^m$, then $m = 2.9 \pm 0.8$. If all pairs at low velocities and $r \leq 20h^{-1}$ kpc merge, then the average galaxy mass would be 32% smaller at $z = 0.4$ than locally.
1. INTRODUCTION

Pairs of galaxies at separations of less than 10–20$h^{-1}$ kpc comprise a small fraction, about 3%, of the present day galaxy population. Many close pairs of galaxies (*e.g.* Arp and Madore 1986) are disturbed, sometimes grossly, by gravitational interaction with a neighboring galaxy (Toomre 1977, Larson and Tinsley 1978). The distorted morphologies can be understood if the infalling galaxies are on orbits close to parabolic, which, in the presence of dynamical friction, implies that most close pairs will merge to produce a single galaxy within $10^9$ years (*e.g.* Toomre 1977, Barnes 1988). The impact of merging on galaxy numbers and masses is a small correction, of order 10%, if it occurred at a uniform rate in the past; however, a number of straightforward arguments predict a rapid rise of merging with redshift within any gravitational instability theory for the formation of galaxies. Toomre (1977) shows that if the distribution of marginal pairwise binding energies is a constant, then the rate of binary mergers increases into the past as $t^{-5/3}$, corresponding to $(1 + z)^{5/2}$ in an $\Omega = 1$ Universe. Somewhat more general considerations, using the Press-Schechter (1974) formalism and including a decoupling from the merging hierarchy, indicate that the rate of merging is proportional to $(1 + z)^m$, where $m \simeq 4.5^{0.42}$ at low redshift (Carlberg 1990) for a fixed mass spectrum. Extrapolation of present day merger rates using functions with such a strong redshift dependence can have a dramatic effect on the galaxy population; such considerations imply that $L_*$ galaxies might be relatively rare beyond $z = 1$ (Broadhurst, Ellis and Shanks 1988; Rocca-Volmerange and Guiderdoni 1990; Carlberg and Charlot 1990; Cowie, Songaila, and Hu 1991; Broadhurst, Ellis, and Glazebrook 1992; Carlberg 1992), although this conclusion is very sensitive to the normalization and redshift dependence of the merger rate.

Zepf and Koo (1989) undertook a study of faint galaxy pairs based on KPNO 4m plates. They found 39 paired galaxies with separations less than 4.5″, drawn from a total population of 1055 galaxies with $m_J \leq 22$. A comparison with low redshift pair samples led them to conclude that the merger rate rises as $(1 + z)^{4 \pm 2.5}$, under the assumption that the pair redshift distribution is similar to that observed in the field; furthermore, they noted that many of the pairs showed evidence of distortions that might arise from tidal effects. A recent study of close pairs using HST data (Burkey *et al.* 1994) finds that the merger rate depends on redshift as $(1 + z)^{2.7}$, in agreement with the above. Indirect evidence that the rate of merging does indeed rise rapidly with redshift can also be inferred from a variety of galaxy phenomena believed to be related to mergers – for example, quasars (Boyle *et al.* 1988), IRAS galaxies, (Lonsdale *et al.* 1990), and the Butcher-Oemler effect (Dressler and Gunn 1983, Butcher and Oemler 1984, Lavery and Henry 1988, Lavery, Henry, and McClure 1992).

The redshift distribution of a magnitude-limited survey of pairs of galaxies could be quite different from that of the field, for at least three reasons. If paired galaxies are, on average, more luminous than field galaxies (perhaps as a result of induced star formation) then their mean redshifts will be higher. However, a magnitude-limited survey of pairs of galaxies that are about to merge may have somewhat lower mean masses than field galaxies (if pair luminosity enhancement is primarily concentrated in intrinsically low luminosity galaxies). On the other hand, if pairs have the same luminosities as field galaxies, then selecting pairs at a fixed angular separation favors pairs at low redshift, because $\xi(\theta d_A(z))$, the real space correlation function, decreases along the line of sight. (Here $d_A(z)$ is the angular diameter distance.) For the limiting case of no luminosity
evolution, the numbers of physical pairs per unit volume, \( n_p(z) \), are distributed (for an \( \Omega = 1 \) Universe) as

\[
n_p(z) \propto (1 + z)^{-\frac{2}{3} - \epsilon + \gamma}[1 - (1 + z)^{-\frac{2}{3}}]^{1-\gamma}n^2(z),
\]

(1)

where \( n(z) \) is the redshift distribution of single galaxies, the correlation function is modeled to evolve as \((1 + z)^{-3-\epsilon}\) (e.g., Efstathiou et al. 1991), and the real space correlation function \( \xi \propto r^{-\gamma} \). For the relatively shallow depths of interest here, \( z \simeq 0.3 \), the average redshift of the pair distribution is expected to be about 10% smaller than that of the field. We conclude that the average redshift of pairs, compared to that of the field, may be an interesting constraint on any differential luminosity evolution of the pairs. (Nevertheless, the effect of equation (1) could potentially be a 50% reduction in mean redshift for samples that have a significant fraction of their population spread beyond \( z \gtrsim 1 \).)

The main goals of this paper are to compare the redshift distribution of close pairs and the field, and to estimate the rise in the merger rate with redshift using a CCD selected sample of pairs both with and without redshifts. The next section discusses our selection procedure and observations. Section 3 contains our observational results (redshifts, colors, and angular correlation function). The implications of these data for the evolution of galaxies in mass and luminosity are discussed in §4.

2. PAIR SELECTION AND OBSERVATIONS

There are several straightforward considerations in constructing a sample of galaxy pairs for a small redshift survey. The sky density of physical pairs with separations less than some small angle \( \theta \) is \( N_p = N_0^2(f) \int_0^\theta (1 + \omega(\theta))2\pi\theta d\theta \) at flux level \( f \). The angular correlation function, \( \omega(\theta) \), can be accurately represented as a power law with slope near \( 1 - \gamma \simeq -0.8 \). The amplitude scales with depth in a approximately Euclidean manner (Maddox et al. 1990, Pritchet and Infante 1992) - i.e., as \( \omega(\theta) \propto \theta^{-\gamma+1}f^{\gamma/2} \). The sky density of faint galaxies brighter than magnitude \( m \) rises as \( \log n(< m) \propto 0.45m, \) or \( n_0(> f) \propto f^{-1.25} \). In the regime where \( \omega(\theta) > 1 \), the surface density of physical pairs at fixed angular separation \( \theta \) is proportional to \( n_0^2(> f)\omega(\theta) \), or \( n_p \propto f^{-1.35} \) - i.e., the number of pairs brighter than \( m \) obeys \( \log N_p \propto 0.54m \). Thus the close pair count rises somewhat faster with magnitude than the number of galaxies - a fact which has an interesting implication for the optimal magnitude at which to observe faint physical pairs. For some fixed total observing time \( T \) with a multiobject spectrograph, the optimal exposure time \( t \) on each field is clearly that which maximizes the rate \( R = n_p/t \) at which useful pair spectra are acquired. Assuming that all spectra above some limiting continuum signal-to-noise ratio have measurable redshifts, then one finds that, in the read noise limit, the rate \( R \) is given by \( R \propto t^{0.35} \), whereas in the sky noise limit, \( R \propto t^{-0.33} \). Therefore the total number of pairs will be optimized for pairs selected brighter than the magnitude at which the spectra begin to be sky-noise dominated \( (V \simeq 22 \text{ in our case}) \).

The field galaxies at \( V \approx 22 \) have a median redshift of \( z \approx 0.35 \) (Colless et al. 1990, Lilly et al. 1991), sufficient for some redshift leverage on the merger rate–redshift relation. At this redshift, the field galaxy population is significantly different than that observed locally: it is bluer, and the luminosity density is about 3 times higher (Colless et al. 1990, Lilly et al. 1991, Eales 1993) (even though the characteristic luminosity \( L^* \) is about the same as observed locally).
For our purposes pairs should ideally be defined as those objects that are doomed to merge; however, for projected data in a continuous clustering hierarchy the definition of a pair is somewhat arbitrary. A reasonable operational definition is to select pair candidates at angles such that \( \omega(\theta) \gtrsim 1 \) (i.e. \( \gtrsim 50\% \) probability that the pair is physical and not projected). At \( V = 22.5 \) the amplitude of the angular correlation function is \( \log \omega(1^\circ) \simeq -2.5 \), or \( \omega(1'') = 2 \) (Pritchet and Infante 1992), implying that \( \omega(\theta) \gtrsim 1 \) for \( \theta \leq 3'' \) (for \( \omega(\theta) \propto \theta^{-0.8} \)). The pair density on the sky is quite low: the expected number of paired galaxies with \( \theta \leq 6'' \) (calculated by extrapolating the Pritchet and Infante 1992 correlation function) is about 1.5 pairs per \( 6 \times 5 \) arcminute field available for spectroscopy. To increase our chances of obtaining pair spectra, pairs were preselected from the same plates as used for the “CFHT North Galactic Pole Survey” (Infante and Pritchet 1992). Because of concerns regarding the separation of close pairs in the original APM image mode data, we ran the Kron (1980) galaxy finding and photometry algorithms on scans of the central regions of the plates. To obtain a reasonable number of pairs we selected all paired galaxies with separations \( \theta \leq 8'' \) (rather than the 3'' criterion discussed above). Based on the Pritchet and Infante (1992) correlation function, one might anticipate that \( \sim \frac{1}{3} \) of all pairs with separations of 8'' and V magnitudes \( \leq 22.5 \) will be physical. For \( V \leq 21.5 \) this fraction will rise to \( \sim 60\% \), and to \( \sim 80\% \) for pairs chosen with a separation in the range 2–8''.

Chosen pairs were all brighter than \( J = 22.5 \) in photometry done on the APM scan data from Infante and Pritchet (1992). We then selected fields to (i) maximize the number of pairs (at least 2 pairs per field, never more than 3), and (ii) preselect (where possible) pairs with similar orientation for spectroscopy. Note that this selection procedure will bias upwards the number of small separation pairs. Our original selection procedure (magnitude, separation, and visual check) identified 110 pairs in an area equivalent to 80 spectroscopy fields (i.e. 1.4 pairs per field). On the basis of the average numbers of pairs selected (~2.5 per field) and expected (~1.4 per field), our procedure should result in a boost of approximately 60\% in the number of close pairs over that expected in purely random fields. However, we show in §3 that the presence of these preselected pairs in our fields actually has only a small effect on our computed correlation functions (because the correlations of close pairs turn out to be much stronger than expected).

Using the above considerations to choose fields, observations were acquired at the Canada-France-Hawaii Telescope in 1992 March using the Marlin multi-object imaging spectrograph in conjunction with a thick, front-side illuminated, Ford Aerospace/SAIC 1024\(^2\) CCD (read noise 6.4 e\(^-\) pixel\(^{-1}\); peak quantum efficiency \( q_{max} \simeq 40\% \) at 6500Å; \( q = \frac{1}{2} q_{max} \) at 5000Å and 8000Å). Imaging observations were acquired of seven of our preselected fields, each approximately \( 6' \times 6' \) in area, through Johnson V and Kron-Cousins I filters (exposure times of 15 min in each filter).

The imaging data were used to design a slitlet mask for each field, using software available at the telescope. First, preselected pairs (see above) were identified on the images, and as many pair galaxies as possible were assigned a slit width (1.5'') and length (nominally 15''). (It was not possible to obtain spectra of all galaxies in pairs, since \( \gtrsim 50\% \) of them had orientations that would have resulted in overlapping spectra.) Once the pairs had been assigned slits, the rest of each field was filled with field objects, many of which were below our expected spectroscopic completeness limit of \( V \approx 22 \). The final data file containing slit coordinates was sent to a computer-controlled laser punching machine (“LAMA”), which produced the final slitlet mask. Spectroscopy was then obtained over a useful wavelength range \( \lambda \lambda 5000–8000 \), with a dispersion of \( 7.7 \text{Å pix}^{-1} \) and slits
1.5″ wide and usually 10″–15″ long. The total spectroscopic integration time per field was 2 hours, spread over 4 individual 30 min exposures. Short (60 s) direct images were taken through the mask (at the beginning and in the middle of each 2 hour sequence of exposures), to check the alignment of objects in the masks, and hence test for flexure. Arcs were acquired at the beginning and end of each 2 hour integration on a field.

Spectra were extracted using the IRAF\textsuperscript{2} \texttt{apextract} package. Redshifts were obtained by identifying two or more of [OII] $\lambda 3727$, 4000Å break, H$\beta$ $\lambda 4861$, [OIII] $\lambda \lambda 4957,5007$, Mg b $\lambda 5180$, and in some cases H$\alpha$ $\lambda 6563$. The continuum shape also played a role in checking redshifts obtained from features and breaks. A quality index $Q$, ranging from 1 (highest quality) to 6, was assigned to each redshift. Most of the analysis below refers to redshifts with $Q \leq 3$, although including $Q = 4$ redshifts changes none of our conclusions.

The imaging fields were later analyzed using photometry and image classification loosely based on the Kron (1980) algorithm. At $V \leq 22.5$ (and $I \leq 23$) our survey contains 1062 objects, of which about 60% are galaxies, in an area of about $9 \times 10^5$ square arcseconds (some area was lost due to internal reflections from bright stars). Internal photometric errors are about 0.1 mag at $V=22.5$ and $I=22$. The image quality is good, 0.8″ in the field center, but degrades to 1.5″ in the field corners.

3. OBSERVATIONAL RESULTS

The average properties of the pairs (chosen to have $\theta \leq 6''$) and field sample are given in Table 1. The second column gives the number of objects placed in slits (excluding stars and bad extractions), and the third column gives the number of objects, $N_z$, for which we were able to obtain redshifts. The pair redshift sample is $8/14 = 57\%$ complete, and the field is about $28/63 = 44\%$ complete (for $V \leq 21.5$). There are at least two reasons for this low completeness. (i) The CCD that we used had poor sensitivity in the blue, with essentially no response below $\sim 4500\AA$, and only $\sim 1/3$ of peak response at 4800Å. This made the 4000Å break and [O II] $\lambda 3727$ impossible to detect for $z < 0.1$ objects, and very difficult at $z \lesssim 0.2$. Interpolating between the results of Colless \textit{et al.} (1990) and Broadhurst \textit{et al.} (1988), we find that approximately $1/3$ of the galaxies in our $V < 21.5$ sample should lie at redshifts $z < 0.2$, compared with $5/38=13\%$ actually observed. Our overall completeness for objects brighter than $V = 21.5$ and with $z \geq 0.2$ therefore rises to $\sim 60\%$. (ii) The information in Table 1 is a fairly conservative cut of objects with secure redshifts. Including the next quality level of redshifts increases the completeness to 61% at $V \leq 21.5$, or $\sim 80\%$ for objects with $z \geq 0.2$. (We note in passing that such a change in redshift quality has hardly any effect on the mean redshift, mean color, or mean line fluxes quoted in Table 1.)

The fourth column of Table 1 gives the average redshifts for $V < 21.5$ and $V < 22.5$; these are a little higher than the values of 0.25 to 0.35 expected for the two magnitude ranges (Colless \textit{et al.} 1990). Apart from one extragalactic HII region, the lowest redshift detected is 0.137, a consequence

\textsuperscript{2} IRAF is distributed by the National Optical Astronomical Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.
Table 1: Average Properties of Paired and Field Galaxies

| Sample          | N$_{slit}$ | N$_z$ | $\langle z \rangle$ | $\langle V \rangle$ | $\langle V-I \rangle$ | $\langle L(\text{O II}) \rangle$ [$h^{-2}$ erg s$^{-1}$] |
|-----------------|------------|-------|---------------------|---------------------|------------------------|-------------------------------------------------|
| $V \leq 21.5$ pairs | 14        | 8     | 0.28±0.03           | 20.5                | 1.19±0.13              | 2.4 ± 1.3 × 10$^{40}$                             |
| $V \leq 21.5$ field | 63        | 28    | 0.36±0.03           | 20.7                | 1.34±0.09              | 1.8 ± 1.1 × 10$^{40}$                             |
| $V \leq 22.5$ pairs | 24        | 14    | 0.42±0.05           | 21.1                | 1.41±0.15              | 4.6 ± 1.9 × 10$^{40}$                             |
| $V \leq 22.5$ field | 97        | 38    | 0.37±0.03           | 21.1                | 1.33±0.09              | 2.3 ± 1.4 × 10$^{40}$                             |

Note: all errors are errors in the mean.

of the poor sensitivity of our CCD below 4500Å, as discussed above. The dispersion about the mean redshift is about 0.16 for both field and pair samples.

3.1 Redshift Distribution

The most significant result arising from the redshift data is that the average redshifts of the pair and field samples are the same to within $\Delta z/z \lesssim 0.1$. This requires that both populations have similar characteristic luminosities: the intrinsic luminosity of the two samples is identical to within 40%. (Formally the $V < 21.5$ sample places an even more stringent constraint on luminosity evolution of the pairs sample, because $\langle z \rangle_{\text{pair}} < \langle z \rangle_{\text{field}}$. Nevertheless, this result must be viewed with some caution because of the small number of redshifts for $V < 21.5$ pairs, and because of subclustering in these redshifts.) Overall, our redshifts place a powerful constraint on differential luminosity evolution between the two populations. (As noted in §1, the bias introduced into pair selection because of the correlation function is much smaller than this.)

3.2 Colors and Luminosities

Column 5 of Table 1 gives the average magnitude of the galaxies, and column 6 gives the mean color and the standard deviation of the mean. In the $V \leq 21.5$ sample the pairs are bluer than the field, but the difference is at the 1σ level. (The colors have not been $k$-corrected, but this should have little effect on the above result because the mean redshifts of the samples are the same.) Color differences of $|\Delta(V - I)| \gtrsim 0.2$ magnitudes are nevertheless ruled out.

The average luminosity in the [O II] 3727Å line, column 7, is calculated (assuming that non-detections have zero line luminosity) in an $H_0 = 100h, \Omega = 1$ cosmology. There is no significant difference in this quantity for the field and pair samples; this result is perhaps not too surprising, given the fact that fewer than 40% of the pairs and 20% of the field galaxies have detections. Perhaps the only difference that is notable in the [O II] $\lambda$3727 properties of the survey is that detections are twice as frequent in the pair sample as in the field sample (5/14=36% for pairs versus 13/70=19% for field objects at $V < 21.5$; 9/24=38% for pairs versus 16/104=15% for field objects at $V < 22.5$).

There are 7 pairs for which both members of the pair possess redshifts; 5 of these pairs belong to our “pre-selected” sample, whereas 2 were “serendipitous”. (One “pair” is actually a triple.) (Since our sample of pairs was selected using the [very faint] cutoff magnitudes $V \leq 22.5$
and \( I \leq 23 \), and because of orientation effects, it is not surprising that many pairs possess only a single redshift.) Three of the pairs with full redshift information have \( \Delta z \leq 0.002 \), one pair has \( \Delta z = 0.031 \), and the other two are separated by \( \Delta z > 0.2 \): that is, three pairs are physical, whereas four are projected. The redshifts of the physical pairs are 0.378, 0.412, and 0.586. Considering that pairs were selected on the basis that \( \omega(\theta) \gtrsim 0.5 \), it is entirely to be expected that of order half of the pairs should be physically associated.

### Table 2: Angular Correlations

|                  | \( V_f < 21.5 \)   | \( V_f < 22.5 \)   | \( I_f < 21.5 \)   |
|------------------|---------------------|---------------------|---------------------|
| \( \omega(< 6'' \))\) | 4.80 ± 1.19         | 2.06 ± 0.41         | 1.07 ± 0.29         |
| \( \omega(6'' - 24'' \))\) | 0.25 ± 0.14         | 0.09 ± 0.06         | 0.18 ± 0.05         |
| \( \omega(< 6'')/\omega(6 - 24'') \)\) | 19.2                | 24.0                | 5.9                 |
| \( N_p(< 6'') \)\) | 24                  | 56                  | 52                  |
| \( N_p(6'' - 24'' \)\) | 80                  | 306                 | 514                 |
| \( N_p(< 6'')/N_p(6 - 24'') \)\) | 0.30±0.07           | 0.18±0.03           | 0.10±0.02           |

#### 3.3 Angular Correlations

Table 2 gives the data for the small separation end of the angular correlation function, derived from our imaging observations. The samples marked with a subscript \( f \) have been selected to be “fuzzy”: that is, their Kron (1980) \( r_2 \) parameters have been preselected (using \( r_2 \geq 1.8 \) for this data) to remove (unclustered) stars. (Note that there may be some compact galaxies which are excluded by this criterion.)

A detailed calculation shows that the \( \theta < 6'' \) bin should have about \( 15 \times \) fewer pairs than the larger \( 6 < \theta < 24'' \) bin (assuming a power-law angular correlation function with power-law slope \( \delta = 0.8 \) and \( \omega(3'') = 1 \), and that galaxies closer than \( 3'' \) cannot be distinguished). (Note that we find no pairs with separations < 1.5''.) The observed ratios of pairs are in fact ~3–5 times larger than this for the \( V \) samples (with the larger excess arising from the most reliable \( V_f < 21.5 \) sample). The correlation function, \( \omega(< 6'' \))\), is expected to be 2.6 times larger than \( \omega(6'' - 24'') \) (under the same assumptions as above). In fact the observed correlations in the \( V \) band are a factor of 7–9 times larger than expected in the innermost bin (a factor of 7 for the \( V < 21.5 \) sample). Excess correlations for the \( I_f < 21.5 \) sample are smaller, but still statistically significant (approximately a \( 2\sigma \) excess in the pair ratio \( N_p(< 6'')/N_p(6 - 24'') \)). The lower excess correlations in the \( I \) band could be due to the higher mean redshift of this sample, or to the fact that the pairs are slightly bluer than the field (at least for the \( V < 21.5 \) sample).

These excesses of close pairs (over what would be expected from an extrapolation of \( \omega(\theta) \) at larger \( \theta \)) are even more significant if \( \delta < 0.8 \) (e. g. Maddox et al. 1990), or if (as might be expected) there is incompleteness in the \( \theta < 6'' \) bin. (At the mean redshift of the sample, \( 6'' \) corresponds to a
physical separation of $19h^{-1}$ kpc for $\Omega = 1$.) It is interesting to note that there is a weak indication of excess small scale correlation at similar separations at low redshifts (Davis and Peebles 1983), although the statistical significance of this result is unclear.

The bias that would result from our field selection (§2) appears to fall far short of explaining the observed excess of close pairs. Only two of our preselected pairs survive the separation ($\Delta \theta < 6''$) and morphology ($r_{-2} > 1.8$) cuts that were used in Table 2; removing these two pairs would have no effect on the significance of the excess of correlation power at small separations.

The images of all the close pairs were examined for signs of distortions and interactions. Although some of the galaxies have features that could be created in tidal distortions, few of the galaxies are strongly distorted. A sample of nearby pairs has been constructed from the UGC catalog (Nilson 1973) with the same projected physical separation; only a small percentage of the equivalent close pairs of galaxies are classified as peculiar (3 of 140) or uncertain (6 of 140). (This nearby pair sample is discussed further below.)

4. IMPLICATIONS FOR MERGER RATES AND MASS EVOLUTION

In this section we examine the consequences of our observations for simple merger models of galaxy evolution. We argue below that mergers must be taking place in our pair population, and from this infer that mergers must have taken place at a significant rate in the field population as well. Formally, none of our observations (mean redshift, colors, line strengths) demand that these mergers cause star formation. However, we argue below that our observations are in fact consistent with models in which mergers induce evolutionary brightening of both the paired galaxies and the field population.

4.1 Pair Fraction and Merger Rate

The fraction of galaxies that are members of $\theta < 6''$ pairs is about 14% of our sample (30 of 196 for $V < 21.5$, and 52 of 410 for $V < 22.5$). We estimate that about 1/2 of these are physical pairs, based on our redshift data (3 of 7 physical pairs) and the measurement that $\omega(\theta) \simeq 2$ for these pairs. Therefore about 7% of the faint galaxies in our sample at $z \simeq 0.4$ are in physical pairs with separations projecting to $19h^{-1}$ kpc.

How does this result compare with the fraction of close pairs found by Burkey et al. (1994) in deep HST images? Their fraction of galaxies in pairs is 34%, for galaxies in the magnitude range $18 < I < 22$ and separations $0.5'' - 4''$. If we assume $\omega(\theta) \simeq 2 - 5$ for $\theta \leq 6''$ (as in Table 2), and extrapolate $\omega(\theta)$ to smaller separations using $\delta = 0.8$, we would predict fractions of galaxies in pairs around 12–14% — a factor of 2.6× smaller than observed by Burkey et al.. Therefore the fraction of galaxies in close pairs, and the correlation function, is increasing much more steeply at small separations than a canonical power-law slope of $\delta = 0.8$ would predict. This is broadly consistent with the fact that our data also shows excess correlation power compared to a power-law fitted at larger separations.

At separations of $\lesssim 20h^{-1}$ kpc, interacting pairs should quickly merge. Toomre (1977) estimates that the time to merge is typically 0.5 Gyr for such objects; this estimate should be relatively conservative, since the orbital time for a 200 km s$^{-1}$ rotation velocity is $0.4h^{-1}$ Gyr at this distance. The merger timescale for the population of faint galaxies as a whole is therefore
$t_{mg}(z = 0.4) \simeq 0.5f_{mg}^{-1}$ Gyr, or 7.1 Gyr. For $H_0 = 50$, this is essentially identical to the Hubble time at $z = 0.4$ (7.9 Gyr), implying that such a large rate of merging will have a significant impact on the average masses of galaxies. Note that all merger rates scale with the assumed 0.5 Gyr for pairwise mergers. This is likely to be a lower limit, with mergers occurring more slowly in groups where tidal fields help to delay merging.

A low redshift sample with comparable pair properties to our faint galaxy sample can be constructed from the (angular diameter limited) UGC catalog, which is statistically complete to $B = 14.5$ (Nilson 1973). The average redshift (of the galaxies in the Nilson catalog which have redshifts) is 0.007 (2100 km s$^{-1}$). At this redshift $19h^{-1}$kpc projects to 192$''$. Restricting the catalog to objects with $B < 14.5$, with measured sizes in both $B$ and $R$, we find 140 paired galaxies of 3066 in the sample, or a fraction of 4.6%. Taking all of these to be physical pairs, we estimate $t_{mg}(z = 0) = 11$ Gyr, where we again assume that the timescale for an individual merger is 0.5 Gyr (as for the faint pair sample).

Although projection is not a problem for nearby galaxy pairs, some physically close galaxies will be moving at such high relative velocities that they are unlikely to merge. Of the 70 UGC pairs, there are 23 for which both galaxies have redshifts; only 13 of these have line of sight velocity differences less than 350 km s$^{-1}$, and hence are likely to merge (the average velocity difference of the “$< 350$ km s$^{-1}$” group is 107 km s$^{-1}$, compared to 570 km s$^{-1}$ for the “$> 350$ km s$^{-1}$” group). Applying this fraction, 0.56, to the 140 close galaxies, reduces the number likely to merge to 79, which decreases $f_{mg}$ to 2.6%, and increases the merger timescale to 19 Gyr. It is interesting to note that 57% of the UGC close pairs are E or S0 galaxies, whereas only 16% of the catalogue has these morphological types. Not surprisingly, 80% of the high velocity pairs are E or S0 galaxies. It is noteworthy that none of the galaxies in the 13 close pairs with small pairwise velocities is classified peculiar, although there are 2 irregulars.

The timescale for merging at the current epoch found here, 19 Gyr, is substantially shorter than implied in Toomre’s (1977) discussion (but see Carlberg and Couchman 1989). The principal difference between these two results is that Toomre demanded that merging objects be severely distorted, with long tidal tails. In fact, there are many more interacting objects in the Arp and Madore (1986) catalog (by a factor of 5 or so) which are likely to merge, yet which lack such conspicuous evidence of interactions.

### 4.2 Evolutionary Effects

The similarities of the faint galaxy pair and field populations have two possible explanations. Either the presence of a close companion has no effect on the color or luminosity of a galaxy, or, if a close companion leads to interactions which boost the star formation rate (as argued by Larson and Tinsley 1978), then interactions must be so frequent that most faint galaxies in the field have recently undergone interactions. At redshift $z \approx 0.3$ the luminosity density, roughly proportional to the star formation rate, is about 3 times higher than at the current epoch (Broadhurst et al. 1988, Lilly et al. 1991, Eales 1993). The following crude calculation shows that the small fraction of galaxies in close pairs, $\sim 7\%$ here, could be the source of all the enhanced star formation in the field. The Larson and Tinsley (1978) model for the B luminosity of a burst is approximately fit by

$$L_b/M = 0.9t^{-0.9},$$  

(2)
where $t$ is measured in units of Gyr, $M/L$ is in solar units, and $L$ is measured in the (rest-frame) $B$ band. The ratio of the total luminosity of a galaxy having a star formation burst of age $t_b$ to the average luminosity of post-starburst galaxies of maximum age $t_m$ is

$$
\frac{L_b}{\langle L \rangle} = \frac{T^{-0.9} + M_0/M_b}{10^{1.2T^{-0.1}} + M_0/M_b},
$$

(3)

where $T = t_b/t_m$, and $M_0/M_b$ is the ratio of the mass of the underlying pre-existing population to the mass of stars formed in the burst.

Equation (3) allows an upper limit to be set on what fraction of an average pairs’s stellar mass is being formed in the interaction, based on keeping $L_b/\langle L \rangle \leq 1.58 \times 10^{-5}$ (the limit implied by the redshift distributions). For interactions occurring at a uniform rate, $t_b/t_m$ can be set to the fraction of interacting galaxies, 7%. Using Equation (3) with $t_b/t_m = 0.07$ gives $M_0/M_b \geq 12$, which sets the upper limit to the fractional burst mass, $M_b/M_0$, as less than 8%. If the underlying old population continually forms stars, then it has a higher luminosity per unit mass than a old pure burst, which could easily lower this limit by a factor of 2. Therefore, induced star formation in close pairs cannot dramatically change the mass of a galaxy–close pairs at $z \approx 0.4$ are not “protogalaxies”.

The cumulative effect of interactions over the lifetime of the galaxy could be a dominant source of its stellar mass, if each interaction does induce the allowed limit of star formation. That is, if 8% (or 4% for continuous star formation) of the stellar mass is formed in each interaction, and all the field galaxies are “post interaction”, which is allowed since the ratio of the interaction time of 0.5Gyr to the age of the universe at $z \approx 0.4$ is about 0.06, then the upper limit to the accumulated burst mass is 100 (50)%). Therefore, most of the mass of a typical galaxy could be built up as a result of interaction induced star formation (assuming that sufficient gas is always available). Greatly improved constraints will be possible with a larger sample. The data presented here includes the “interaction formation” hypothesis only as an upper limit.

### 4.3 Redshift Dependence of Merger Rate

The relative rates of merging at $z = 0$ and $z = 0.4$ can be compared without knowing the timescale for merging. We estimate that 7.0±1.5% of the galaxies at $\langle z \rangle \approx 0.4$ are in pairs with the same physical separation and merger probability, and 2.6±0.3% of the galaxies at $z \approx 0$. The ratio of merger rates at these two redshifts is therefore 2.7±0.7, where the uncertainties have been computed by assigning $N^{1/2}$ errors to the number of objects at each redshift. (Note that the error in the fraction of objects in pairs at $z=0.4$ may be larger than derived from $N^{1/2}$ errors, because of uncertainties in the fraction of pairs that are physical.) Assuming a $(1+z)^m$ increase in merger rate with redshift therefore implies that $m = 2.95 \pm 0.8$, in good agreement with $m = 2.7$ derived by Burkey et al. (1994) from HST images.

The merger rate index can be tentatively linked to $\Omega$; low $\Omega$ gives very little growth of structure at late times, although $m > 2$ for any reasonable $\Omega$. The key assumption is that galaxies moving at less than some critical pairwise velocity will merge (Aarseth and Fall 1980); the critical pairwise velocity is comparable to the escape speed. Under the assumption that the pairwise velocity of encounter of two galaxies evolves as expected in hierarchical clustering, $(1+z)^m$, and that the critical velocity remains constant (not completely true for an evolving mass distribution) then it
is straightforward to show that the merger rate index, \( m \), should vary as \( m \approx 4.5\Omega^{0.42} \) (Carlberg 1990) for an unevolving mass spectrum. The rate of change will be reduced if the galaxies become significantly lighter in the past. Allowing for a 32% mass difference between redshift 0 and 0.4 (see below) changes the relation to \( m = 3.2\Omega^{0.57} \). For our measured \( m \), the implied \( \Omega = 0.87 \pm 0.4 \). The large random error means that this is not a very useful constraint on \( \Omega \); clearly a larger sample of pairs could rectify this problem. The other merger model parameters have relatively little effect over this range of redshifts. Certainly the rapid rate of change in merger rate found here argues against a low \( \Omega \) Universe; in such Universes the growth of perturbations “freezes out” at high redshift \( (z \approx \Omega^{-1}) \), so that the present day merger rate is slower and depends more weakly on \( z \).

Figure 1: The merger rate – redshift relation. The \( z = 0.007 \) data comes from close pairs in the UGC catalog. The \( z = 0.4 \) results are from this survey. The lines use the theory discussed in the text, which is based on a generalization of the Press-Schechter formula. The size of the ellipses indicates the approximate spread in the data along each axis. The theoretical predictions (solid lines) depend primarily on \( t_{mg} \), which is assigned values of 13, 26, and 45 Gyr (top to bottom). The two closely-separated lines in the middle show the result of changing \( v_{mg} \) from 280 to 140 km s\(^{-1}\) . Integration under either of the middle lines implies that the average galaxy at \( z = 0.4 \) has a mass that is 68% of that of present-day galaxies. Extrapolating to \( z = 1 \) reduces galaxy masses to 36% of present-day values, assuming that low relative velocity pairs merge.

The merger rates estimated from the UGC catalog and our survey are displayed in Figure 1,
The merger rate per galaxy is given as

\[ R_{mg} = \frac{t_0}{c_n t_{mg}} \gamma \left( 1.5, 0.5 \frac{v_{mg}^2}{v_p(z)^2} \right) \frac{1}{t}, \tag{4} \]

where \( \gamma(a, x) \) is the incomplete gamma function (the integral of a Maxwellian speed distribution), \( v_{mg} \) is the critical velocity for merging, taken to be 280 km s\(^{-1}\), and \( v_p \) is the pairwise velocity dispersion of galaxies, taken to be 600\((1 + z)^{(n-1)/(2n+6)}\) km s\(^{-1}\) (Carlberg 1990). The constant \( c_n \) normalizes the expression to \( t_{mg}^{-1} \) at \( t = t_0 \). We take \( n = -1.5 \) as is indicated by the correlation function and the CDM spectrum for mass scales of 3–10 galaxy masses. This value of \( n \) predicts that the pairwise velocity dispersion evolves as \( v_p(z) \propto (1 + z)^{-5/6} \), a 25% drop out to redshift 0.4.

The critical velocity for merging will evolve as the galaxy masses change; however for \( v_{mg} \propto M^{1/3} \) the inferred drop of \( \sim 30\% \) in the average galaxy mass (see below) is sufficiently small that changes in \( v_{mg}/v_p \) are caused primarily by changes in \( v_p \). For small values of the \( t_{mg} \) this expression exceeds the rate of halo mergers,

\[ R_{mg} = \frac{2}{n + 3} \frac{1}{t}, \tag{5} \]

predicted at larger \( z \). The \( R_{mg} \) plotted in Figure 1 is the minimum of the two expressions, with Equation (4) dominating in the \( 0 \leq z \leq 0.4 \) range where our data lies. The scaling with redshift of Equation (4) should be about right, but the normalization is subject to a lack of almost any knowledge of the details of merging of galaxy size objects in a cosmological context.

The change in the numbers of galaxies as a result of merging is

\[ \frac{dn_g}{dt} = R_{mg} n_g \tag{6} \]

Under the assumption that the baryonic mass content of galaxies may be rearranged but not changed, Eq. 4 implies that the characteristic mass of galaxies decreases as

\[ M_*(z) = M_*(0) \exp \left[ - \int_0^{t(z)} R_{mg} dt \right] \tag{7} \]

with redshift. We make a smooth transition between the two rates by using an inverse quartic interpolation. The model line shown in Figure 1 implies that at \( z = 0.4 \), the characteristic mass of galaxies \( M_*(z = 0.4) = 0.69 M_*(0) \). Extrapolating to \( z = 1 \) predicts that \( M_*(z = 1) = 0.36 M_*(0) \), which is indeed a dramatic change in the population. (However, it should be noted that the uncertainty in this result is very large – nearly a factor of 2 – and depends on the accuracy of the theoretical model.) These estimates of mass changes can be taken as upper limits, since the time to merge may well be longer than the 0.5 Gyr assumed, and since some close pairs may fail to merge, as a result of strong gravitational tides in clusters and groups.

4.4 Companion Galaxies?

The excess small scale correlations discussed in §3 (about a factor of 2 or 3 more galaxies at \( \theta \leq 6'' \) than expected, a result which is more prominent in V than I) have at least two possible explanations consistent with our observed redshift distribution: either they represent a true density
excess, or they are due to a selective brightening only of intrinsically low luminosity companions. At low redshift the correlation function appears to be consistent with a power law on all scales (Lake and Tremaine 1980, Davis and Peebles 1983). At somewhat higher redshifts quasar absorption line studies suggest that galaxies may have associated substructure (Wolfe et al. 1986, Steidel 1993). A luminosity excess for close pairs is predicted in models in which the changes in the field population luminosity density at $z \simeq 0.3$ are due to galaxy interactions and merging (Rocca-Volmerange and Guiderdoni 1990, Cowie et al. 1991, Broadhurst et al. 1992, Carlberg and Charlot 1992, Carlberg 1992). For an unperturbed luminosity function of the form $L^{-\alpha} d \ln L$, with $\alpha \simeq 1$ (approximately the normal Schechter function value) a brightening of a factor of 2, as allowed by our limits on the redshift distributions, increases the numbers above some limiting $L$ by at least a factor of 2.

Our data is consistent with either a density excess or a companion luminosity enhancement. A large, photometrically accurate imaging and spectroscopic survey will be necessary to accurately define the mean properties of these populations, which have large intrinsic dispersions. At the optimal magnitude for pair surveys, $V \simeq 21 - 22$, there are only 100 pairs per square degree, requiring a great deal of sky to be surveyed.

5. CONCLUSIONS

We have 53 redshifts of galaxies drawn from a $V \leq 22.5$ photometric sample of $\simeq 1000$ galaxies. Close pairs are defined as objects closer than 6″ on the sky, for which we have 14 redshifts. The pairs are compared to a sample of nearby pairs assembled from the UGC catalog with the same projected physical separation. The principal result of this study is that the mean redshift of the pair population is very similar to the mean redshift of the field galaxies at the same magnitude limit. This limits the differential luminosity evolution between the field and pairs to less than $\sim 0.5$ mag difference. The small magnitude difference implies that if an average pair has interaction induced star formation, it only adds 8% more stellar mass on the average. Integrated over the lifetime of the galaxy this could account for the entire stellar mass, but as an upper limit, given the observational constraints we have derived.

A second result is that the rise of the fraction of galaxies in close physical pairs implies that the merger rate–redshift relation is $(1 + z)^{2.9\pm0.8}$ over the interval $0 < z < 0.4$. This result is somewhat shallower than that of Zepf and Koo (1989); however it should be more reliable because uncertainties concerning the redshift distribution of the pairs have been removed. When combined with theoretical modeling of the expected merger rate-redshift relation, our observations have two important implications. If all of these galaxies do merge, then the average mass at $z \simeq 0.4$ is reduced by 32%, and by a factor of $\sim 2.7$ at redshift 1 (the latter result depending significantly on the accuracy of the model used for the extrapolation). Secondly, the slope of the merger-rate redshift relation indicates $\Omega \simeq 0.87\pm0.4$. The combination of model dependencies and large random error makes this density estimate less than compelling.

There is an excess correlation at projected separations of $< 20h^{-1}$ kpc. The strong correlation at $r \lesssim 20h^{-1}$ kpc could be either a local bound population, or the result of a luminosity enhancement of intrinsically faint galaxies in close pairs.

There are several limitations inherent in this study. A larger photometric and redshift sample
would allow a conclusive check of the color differences between field and pairs, which are expected to be in the range of 10%, because the field is so much bluer than observed locally. In this study there is no conclusive direct indicator that mergers have taken place, or will take place, other than the (difficult to quantify) distortion morphology; nor is there any direct indication that pairs have excess star formation rates. The relative rate of merging is established to within an accuracy of a factor of two, but the absolute rate is still poorly known, and the impact of merging on the mass function hinges upon an integral over the absolute rate.

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