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# The Merger Rate to Redshift One from Kinematic Pairs: Caltech Faint Galaxy Redshift Survey XI

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## ABSTRACT

The rate of mass accumulation due to galaxy merging depends on the mass, density, and velocity distribution of galaxies in the near neighborhood of a host galaxy. The fractional luminosity in kinematic pairs combines all of these effects in a single estimator which is relatively insensitive to population evolution. Here we use a k-corrected and evolution compensated volume-limited sample having an R-band absolute magnitude of $M_R^{k,e} \leq -19.8 + 5\log h$ mag drawing about 300 redshifts from CFGRS and 3000 from CNOC2 to measure the rate and redshift evolution of merging. The combined sample has an approximately constant co-moving number and luminosity density from redshift 0.1 to 1.1 ($\Omega_M = 0.2, \Omega_\Lambda = 0.8$); hence, any merger evolution will be dominated by correlation and velocity evolution, not density evolution. We identify kinematic pairs with projected separations less than either 50 or 100 $h^{-1}\,$kpc and rest-frame velocity differences of less than $1000\,\mathrm{km\,s^{-1}}$. The fractional luminosity in pairs is modeled as $f_L(\Delta v, r_p, M_r^{ke})(1+z)^{m_L}$ where $[f_L, m_L]$ are $[0.14 \pm 0.07, 0 \pm 1.4]$ and $[0.37 \pm 0.7, 0.1 \pm 0.5]$ for $r_p \leq 50$ and $100h^{-1}\,$kpc, respectively ($\Omega_M = 0.2, \Omega_\Lambda = 0.8$). The value of $m_L$ is about 0.6 larger if $\Lambda = 0$. To convert these redshift space statistics to a merger rate we use the data to derive a conversion factor to physical space pair density, a merger probability and a mean in-spiral time. The resulting mass accretion rate per galaxy ($M_1, M_2 \geq 0.2M_*$) is $0.02 \pm 0.01(1+z)^{0.1\pm0.5} M_*$ Gyr$^{-1}$. Present day high-luminosity galaxies therefore have accreted approximately $0.15M_*$ of their mass over the approximately 7 Gyr to redshift one. Since merging is likely only weakly dependent on host mass, the fractional effect, $\delta M/M \simeq 0.15M_*/M$, is dramatic for lower mass galaxies but is, on the average, effectively perturbative for galaxies above $M_*$.

*Subject headings:* cosmology: large scale structure, galaxies: evolution

## 1. Introduction

Merging is a fundamental mode of stellar mass addition to galaxies. Moreover, merging brings in new gas and creates gravitational disturbances that enhance star formation or fuel a nuclear black hole. The general process of substructure infall may be the rate fixing process for the buildup of a galaxy's stars and consequently may largely regulate its luminosity history. Gravitational forces on relatively large scales dominate merger dynamics which allows direct observation of the mechanism, although with the considerable complication that dark matter dominates the mass. N-body simulations (Toomre & Toomre 1972; Barnes & Hernquist 1992) give the detailed orbital evolution, morphological disturbances and eventual outcomes of the encounters of pairs of galaxies.

The purpose of this paper is to estimate the rate of mass gain per galaxy due to mergers over the redshift zero to one interval. Our primary statistic is the fractional luminosity in close kinematic pairs, which is readily related to n-body simulations and sidesteps morphological interpretation. This approach provides a clear sample definition which is closely connected to the large scale dynamics of merging. In common with all merger estimates it requires an estimate of the fraction of the pairs that will merge and a mean time to merger.

The number of kinematic pairs is proportional to the volume integral at small scales of the product of two-point correlation function, $\xi$, and the luminosity function (LF). The high luminosity galaxies appear to be evolving purely in luminosity (Lilly et al. 1995; Lin et al. 1999), which can be easily compensated. The measured

evolution of $\xi$ suggests that the density of physical pairs should not vary much with redshift, $(1+z)^{0\pm1}$ (LeFèvre et al. 1996; Carlberg et al. 1997; Carlberg et al. 1999). This inference is in notable contrast with the pair counts or morphological typing approaches to merger estimation (Zepf & Koo 1989; Carlberg Pritchet & Infante 1994; Yee & Ellingson 1995; Patton et al. 1997; LeFèvre et al. 1999), which suggest that merging rate by number varies as $(1+z)^{3\pm1}$. HST photometric pairs, with no redshift information leads to a dependence of $(1+z)^{1.2\pm0.4}$ (Neuschaefer et al. 1997).

In the next section we combine the Caltech Faint Galaxy Redshift Survey (CFGRS) and the Canadian Network for Observational Cosmology field galaxy survey (CNOC2) from which we construct evolution compensated, volume-limited, subsamples. In Section 3 we measure the fractional luminosity in 50 and $100h^{-1}\,\mathrm{kpc}$ companions as a function of redshift. The CNOC2 sample is used in Section 4 to relate this wide pair sample to a close pair sample which is more securely converted into a mass merger rate. Section 5 discusses our conclusions. We use $H_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_M = 0.2$ in open and flat cosmologies.

## 2. The CFGRS and CNOC2 Volume-Limited Samples

The CFGRS sample of the HDF plus flanking fields is discussed in detail elsewhere (Hogg et al 1999; Cohen et al. 2000). We use the high coverage subsample lying within a 240 arcsecond radius circle, with a center located at $12^h\ 36^m\ 50^s$ and $62^\circ\ 12'\ 55''$ (J2000). The computed magnitude selection function, $s(m_R)$, (in Cousins R) is accurately approximated as a constant 90% spectroscopic completeness for $m_R < 22.8$ mag with a linear decline to 19% at $m_R < 23.4$ mag, our sample limit. The magnitude weight is $1/s(m_R)$. The CFGRS k-corrections and evolution compensation are here approximated as $k(z) = Kz$ mag from the tables of Poggianti (1997). For galaxies that Cohen et al. (2000) classify as "E" (emission), $K = 1.0$, "A" types have $K = 2.0$ and all types have $K = 1.7$

The CNOC2 selection weights and k-corrections are discussed in Yee et al. (2000). . The evolution of the luminosity function is approximated as a uniform $M_*(z) = M_* - Qz$, with $Q \simeq 1$, (Lin et al. 1999) which we use over the entire CNOC2-CFGRS redshift range.

The kinematic pair fraction is directly proportional to the mean density of the sample and is therefore sensitively dependent on correcting to a complete and uniform sample (Patton et al. 2000a). The most straightforward approach is to impose a strict volume limit. For our primary sample we will limit the CFGRS and the CNOC2 samples at $M_R^{k,e} = -19.8 + 5\log h$ mag, which yields volume-limited samples of about 300 CFGRS galaxies between redshift 0.3 to 1.1 and 3000 CNOC2 galaxies between 0.1 to 0.5. The volume density of the sample is approximately constant at $1.2 \times 10^{-2} h^3$ Mpc$^{-3}$ over the entire redshift range for $\Omega_\Lambda = 0.8$ but rises roughly as $(1+z)^{0.8}$ for $\Omega_\Lambda = 0$. Both the CFGRS and the CNOC2 surveys are multiply masked, which minimizes the effects of slit crowding, however there is still a measurable pair selection function. The CNOC2 catalogue has about a 20% deficiency of close angular pairs. We model the measured angular pair selection weight as, $w(\theta) = [1 + a_s \tanh(\theta/\theta_s)]^{-1}$, where $[a_s, \theta_s]$ is $[0.5, 5'']$ for the CFGRS sample and $[-0.3, 10'']$ for the CNOC2 sample with typical pair corrections being 10%.

## 3. The Pair Fractional Luminosity Fraction

The preferred choice of pair statistic depends on the application (Patton et al. 2000a). Here we are primarily interested in the impact of merging on galaxy mass increase, for which the k-corrected, evolution compensated R luminosity is a stand-in. The rate of merging per galaxy depends on the density of galaxies in the near neighborhood and their velocity distribution. As a practical redshift space estimator, we compute the fractional

luminosity in close kinematic pairs,

$$f_L(z|\Delta v^{\max}, r_p^{\max}, M_R^{k,e}) = \frac{\sum_j \sum_{i\neq j,<\Delta v^{\max},<r_P^{\max}} w_j w_i w(\theta_{ij}) L_i}{\sum_j w_j L_j}, \quad (1)$$

where the weights, $w_i$, allow for the magnitude selection function. Note that the $ij$ and $ji$ pairs are both counted. The ratio has the benefit of being fairly stable for different luminosity limits, self-normalizing for luminosity evolution, identical to a mass ratio for a fixed $M/L$ population. For an unperturbed pair luminosity function it is mathematically identical to the $N_c$ of Patton *et al.* (2000a) although constructed out of somewhat different quantities. The two parameters, $\Delta v^{\max}$ and $r_p^{\max}$, are chosen on the basis of merger dynamics and the characteristics of the sample. The rate of mass increase per galaxy is calculated from this statistical estimator using a knowledge of merger dynamics and the measured correlations and kinematics of galaxy pairs in the sample.

The mean fractional pair luminosity, based on 18 CFGRS pairs and 91 CNOC2 pairs, with $\Delta v \leq 1000\,\mathrm{km\,s^{-1}}$ and $5 \leq r_p \leq 50\,h^{-1}\,\mathrm{kpc}$ pairs is displayed in Figure 1. These kinematic separation parameters are larger than is suitable for reliably identifying "soon-to-merge" pairs. However, they provide a statistically robust connection to those pairs and take into account the lower velocity precision and sample size of the CFGRS relative to CNOC2. The errors are computed from the pair counts, $n_p^{-1/2}$. The measurements of $f_L(z)$ in Figure 1 are fit to $f_L(\Delta v, r_p, M_r^{ke})(1+z)^{m_L}$, finding $[f_L, m_L]$ of $[0.14 \pm 0.07, 0 \pm 1.4]$ for $r_p \leq 50\,h^{-1}\,\mathrm{kpc}$ pairs and $[0.37 \pm 0.7, 0.1 \pm 0.5]$ for $r_p \leq 100\,h^{-1}\,\mathrm{kpc}$, both for $\Omega_M = 0.2, \Omega_\Lambda = 0.8$. The increase with $r_p$ of $f_L$ is consistent with a $\gamma = 1.8$ two-point correlation function. If $\Omega_M = 0.3, \Omega_\Lambda = 0.7$, then $m_L$ at $100h^{-1}\,\mathrm{kpc}$ rises by about 0.05 whereas if $\Omega_M = 0.2, \Omega_\Lambda = 0.0$, then $m_L = 0.50$. The increase is largely as a result of the rise in the implied co-moving sample density over this redshift range.

The merger probability of a kinematic pair depends sensitively on the pairwise velocity dispersion, $\sigma_{12}$, of galaxies. The model pairwise velocity distribution is computed as the

convolution of the correlation function with the distribution of random velocities. The infall velocities are negligible at these small separations and we will assume that the peculiar velocities are drawn from a Gaussian distribution. The measured fraction of the CNOC2 pair sample with velocities smaller than some $\Delta v$, normalized to the value at $1000\,\mathrm{km\,s^{-1}}$, is displayed in Figure 2. The $50h^{-1}\,\mathrm{kpc}$ wide pairs limited at $-19.5$ mag are plotted as open squares, the $20h^{-1}\,\mathrm{kpc}$ pairs limited at $-18.5$ and $-19.5$ mag are plotted as octagons and diamonds, respectively. The upper curve assumes that $\sigma_{12}$ is 200 $\mathrm{km\,s^{-1}}$ and the lower one 300 $\mathrm{km\,s^{-1}}$, which approximately span the data.

## 4. Merger Rate Estimation

The merger rate is best estimated from very close kinematic pairs, $20h^{-1}\,\mathrm{kpc}$ or less, about half of which are physically close and have significant morphological disturbance (Patton et al. 2000a). However the fraction of galaxies in such close pairs is about one percent, giving poor statistics. Since the number of pairs increases smoothly as $r^{3-\gamma}$, where $\gamma$ is the slope of the small scale correlation function, we can use pairs at somewhat larger separations as statistically representative of the close pairs, however we prefer to stay within the radius of virialized material around a galaxy over our redshift range, which is no larger than about $100h^{-1}\,\mathrm{kpc}$. The mass accretion rate from major mergers is therefore estimated as,

$$\mathcal{R}_M = \frac{1}{2} f_L(\Delta v, r_p, z) C_{zs}(\Delta v, \gamma) F(v < v_{mg}) \langle M \rangle T_{mg}^{-1}(z, r_p), \tag{2}$$

where the factor of one half allows for the double counting of pairs, $C_{zs}(\Delta v, \gamma)$ converts from redshift space to real space pairs, F gives the fraction of the pairs that will merge in the next $T_{mg}$ (the "last orbit" in-spiral time from $r_p$) and $\langle M \rangle$ is the mean incoming mass as estimated assuming a constant M/L. For the relatively massive galaxies considered here the dynamical friction is so strong that it is more violent relaxation with little timescale

dependence on the masses. The measured ratio of the numbers of 50 and $100h^{-1}$ kpc pairs to $20h^{-1}$ kpc pairs in the CNOC2 sample is $3.8 \pm 1.0$ and $9.4 \pm 3.0$, respectively, in accord with the expectation of a growth as $r_p^{3-\gamma}$ with the inner cutoff of $5h^{-1}$ kpc.

Not all kinematic pairs are close in physical space. The relation between the kinematic pairs closer than $r_p$ and $\Delta v$ and pairs with a 3D physical distance $r_p$ is readily evaluated by integrating the velocity convolved correlation function over velocity and projected radius and ratioing to the 3D integral of the correlation function. We find that $C_{zs} = 0.54$ for $\Delta v = 1000\,\mathrm{km\,s^{-1}}$ and $\gamma = 1.8$ There is support for this value on the basis of morphological classification, as tested in Patton et al. (1999), where about half of the kinematic pairs exhibited strong tidal features.

The fraction of physically close pairs that are at sufficiently low velocity to merge is a key part of the rate calculation. It is clear that many galaxies will have close encounters which do not lead to immediate mergers, although mergers could of course occur on subsequent orbital passages. The key quantity that we need is the ratio of the critical velocity to merge, $v_{mg}$, to $\sigma_{12}$. The timescale for close pairs to merge is much shorter than the time over which morphological disturbances are clearly evident, by nearly an order of magnitude (Barnes & Hernquist 1992; Mihos & Hernquist 1996; Dubinski Mihos & Hernquist 1999). This is one of our reasons for preferring kinematic pairs as a merger estimator. The simulation results indicate that the time to merge is, on the average, roughly that of a "half-circle" orbit, which at $r_p$ of $20h^{-1}$ kpc at a velocity of 200 $\mathrm{km\,s^{-1}}$ is close to 0.3 Gyr. A straight-line orbit with instantaneous merging would merge in about 0.1 Gyr, although that is not likely to be representative.

To compute the merger probability, $F(< v_{mg})$, we need to know the maximal velocity to merge, $v_{mg}$, at a physical separation of $20h^{-1}$ kpc for a typical $M_*$ galaxy. A not very useful lower bound is fixed by the Keplerian escape velocity at $20h^{-1}$ kpc, $v_c\sqrt{2}\,\mathrm{km\,s^{-1}}$,

where the circular velocity is approximately 200 $\mathrm{km\,s^{-1}}$. An upper bound to $v_{mg}$ is the velocity that an object would have if it is captured into a galaxy's extended dark halo at the virialization radius and orbits to $20h^{-1}\,\mathrm{kpc}$ with no dynamical friction. The virialization radius is approximately at the radius where the mean interior overdensity is $200\rho_c$, implying $r_{200} = v_c/(10H_0)$, or, about $200h^{-1}\,\mathrm{kpc}$ for our typical galaxy. The largest possible apogalactic velocity at $r_{200}$ is $v_c$, which leads to an undissipated velocity at $20h^{-1}\,\mathrm{kpc}$ of $2.37v_c$. Using $\sigma_{12} = 200(300)\,\mathrm{km\,}s^{-1}$ at $20h^{-1}\,\mathrm{kpc}$, we find that the fraction of all physical pairs that merge in one $T_{mg}$ is about 0.40(0.16). Therefore, we will normalize to a merger probability of 0.3, noting the 50% or so uncertainty.

The absolute magnitude limit of $-19.8 + 5\log h$ mag corresponds to $L \geq 0.5L_*$ which contains about 58% of the luminosity for the mean CNOC2 LF, $M_* = -20.4$ and $\alpha = -1.2$. To make our merger rate inclusive of major mergers we normalize to $L \geq 0.2L_*$, which includes 85% of the luminosity. Within the current statistical accuracy, the paired and field galaxies have identical LFs. On the basis of n-body experiments (Barnes & Hernquist 1992) galaxies with masses greater than about $0.2M_*$ will merge in approximately one orbital time.

On the basis of these considerations we find that the rate of mass accumulation of galaxies with luminosities of $0.2M_*$ and above is,

$$\mathcal{R}_M = (0.02 \pm 0.01)M_*(1+z)^{0.1\pm0.5}\frac{F(v_{mg}/\sigma_{12})}{0.3}\frac{0.3\mathrm{Gyr}}{T_{mg}}\mathrm{Gyr}^{-1}, \quad (3)$$

where we have adopted the $100h^{-1}\,\mathrm{kpc}$ $m_L$ value for a flat, low density cosmology and explicitly assumed that the velocity and timescale factors do not vary over this redshift range, as expected at these small scales in a low $\Omega$ universe (Colin Carlberg & Couchman 1997). There is direct evidence that once evolution compensated that the luminous galaxies retain have no evolution in their circular velocities (Vogt et al. 1997; Mallen-Ornelas Lilly Crampton & Schade 1999).

## 5. Discussion and Conclusions

Our main observational result is that for galaxies with $M_R^{k,e} \leq -19.8 + 5\log h$ mag, the fraction of galaxy luminosity in $50h^{-1}$ kpc wide kinematic pairs is about 14%, with no noticeable redshift dependence over the redshift zero to one range. This implies an integrated mass accretion rate of about 2% of $L_*$ per Gyr per galaxy for merging galaxies having $L \geq 0.2L_*$. Our rate is uncertain at about the factor of two level due to uncertainty in the dynamical details of merging for our sample definitions. This merger rate implies a 15% mass increase in an $M_*$ galaxy since redshift one. If the correlations of lower luminosity galaxies are only somewhat weaker than these (Carlberg et al. 1998) then the same $0.15M_*$ merged-in mass causes a 50% mass increase in a $0.3M_*$ galaxy.

There are several issues that require further investigation. First, the rate of merging of similarly selected kinematic pairs should be studied in appropriately matched n-body experiments to better determine the orbital timescales. Second, the absence of a redshift dependence of $\sigma_{12}$ and $v_{mg}$ needs to be observationally checked. Third, the connection between close kinematic pairs and morphologically disturbed galaxies, which does conform to the kinematic pair predictions at low redshift (Patton et al. 2000a), needs to be better understood at high redshift.

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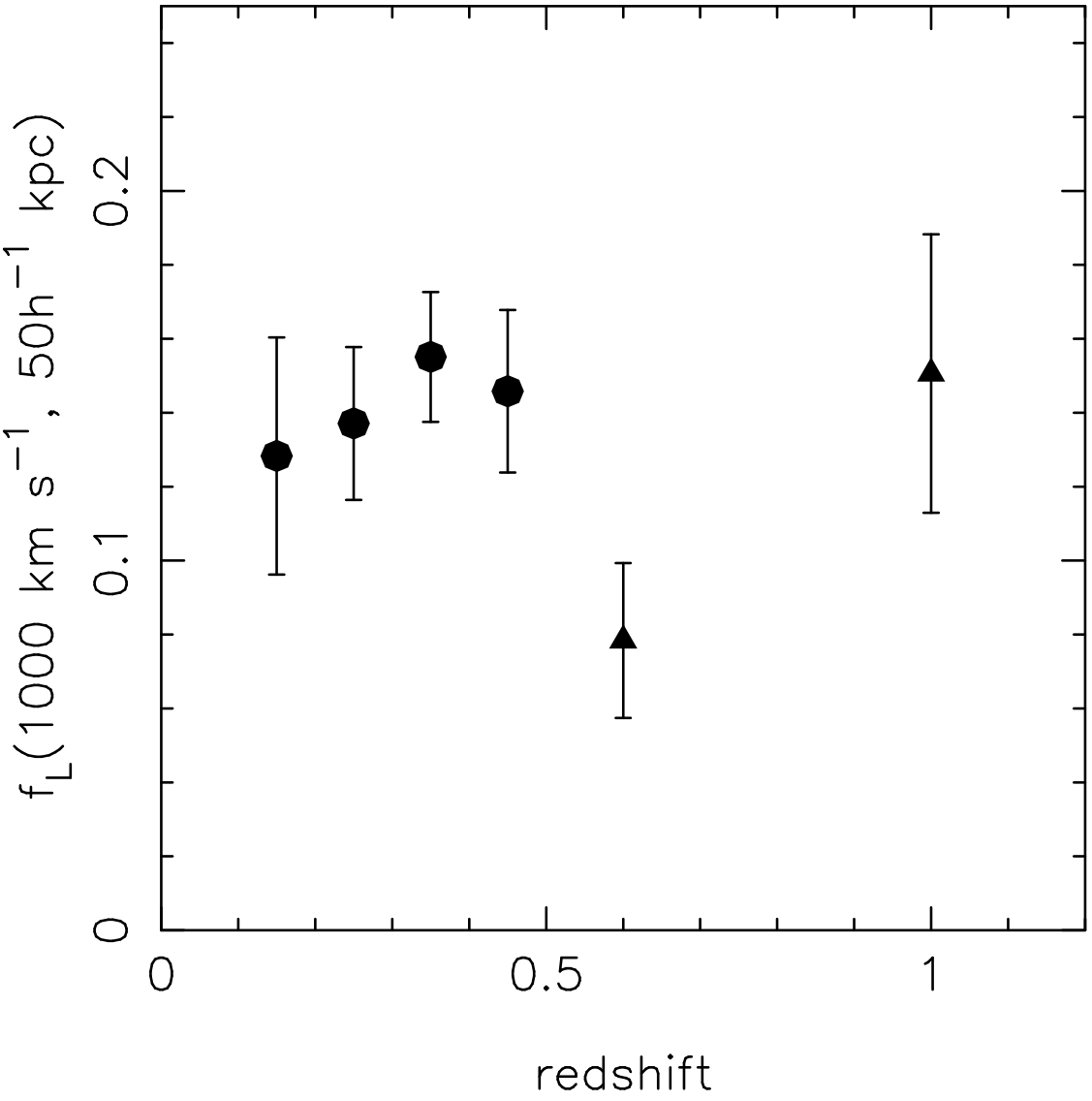
Fig. 1.— The fraction of the sample luminosity in pairs with $\Delta v \leq 1000\,\mathrm{km}\,s^{-1}$ and $5 \leq r_p \leq 50\,h^{-1}\,\mathrm{kpc}$ as a function of redshift. The octagons are from the CNOC2 sample and the triangles from CFGRS.

Fig. 2.— The velocity distribution function for CNOC2 galaxy pairs. The filled points are for $20h^{-1}\,\mathrm{kpc}$ pairs limited at $M_R^{k,e}$ of $-19.5$ mag (diamonds) and $-18.5$ mag (octagons) and the open squares are for $50h^{-1}\,\mathrm{kpc}$ pairs limited at $-19.5$ mag. The lines are the distributions expected for an $r^{-1.8}$ correlation function convolved with Gaussian velocity distribution functions of 200 and 300 $\mathrm{km\,s^{-1}}$, the upper and lower lines respectively.


0
0.1
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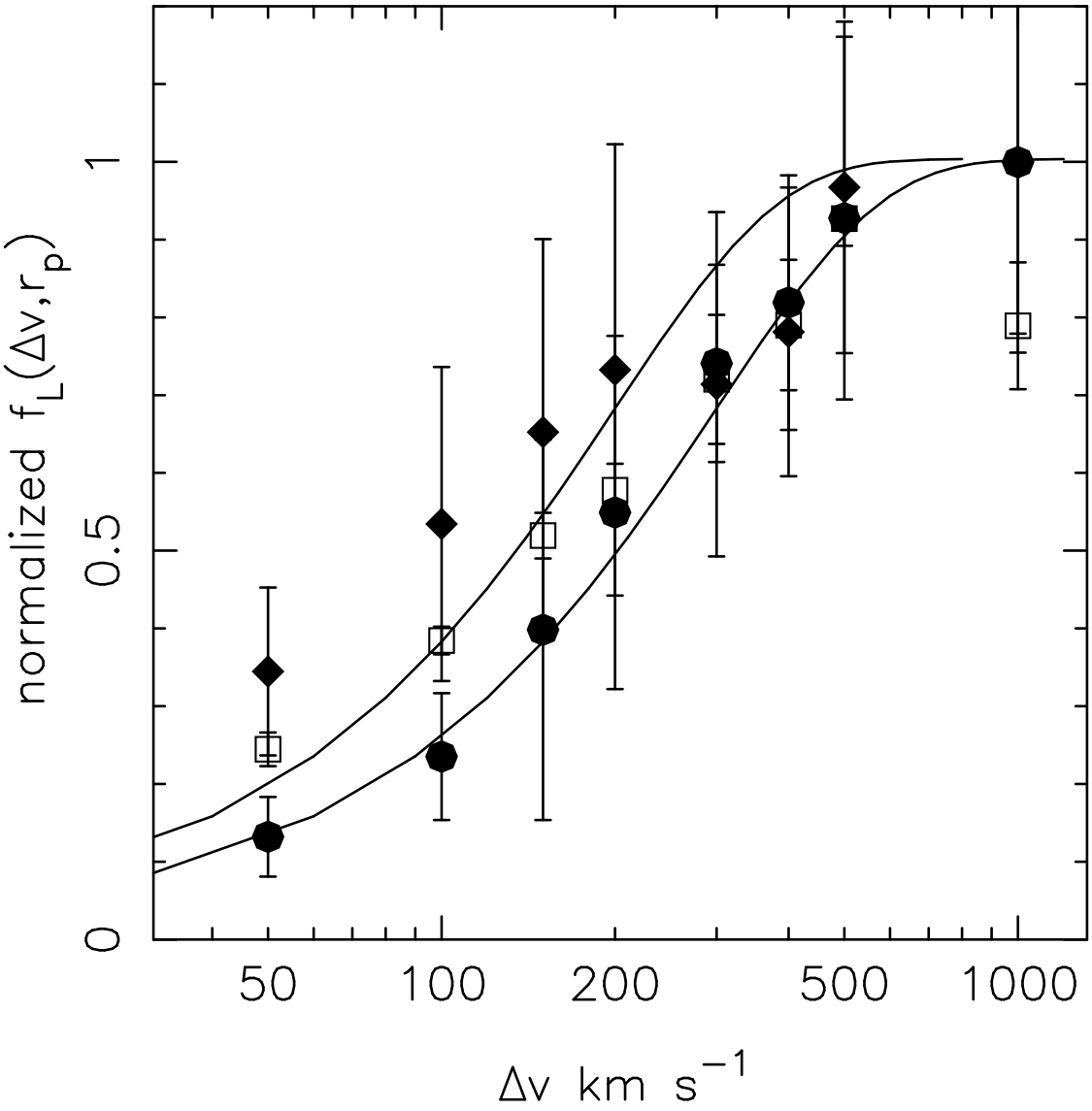
redshift
$f_L$(1000 km s$^{-1}$, 50h$^{-1}$ kpc)


normalized $f_L(\Delta v, r_p)$
0
0.5
1
50
100
200
500
1000
$\Delta v$ km $s^{-1}$