A Catalog of Faint Interacting Galaxies in Pairs and Groups [1]

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ABSTRACT

We have carried out an extensive survey of faint galaxies in order to examine the rise in the merger rate with redshift and to study the statistical relations between close interacting galaxies and the field galaxy population. In this paper we present the catalogs of faint pairs and groups of galaxies of 46 equatorial fields taken with the CTIO 4m prime focus. The data set contains 73,988 galaxies covering a total area of 2.23 deg^2. We have found 1751 isolated pairs and 30 groups of galaxies within $19 < m_R < 22$ and $2'' < \theta < 6''$ in this area. Our results show clearly an increase in pairs and groups of galaxies in comparison to a randomly generated catalog.

Subject headings: galaxies: interactions — galaxies: evolution — catalogs

Astrophysical Journal Supplement Series: Accepted

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1. Introduction

Observations of pairs of galaxies at intermediate redshifts have revealed a larger number of objects in the past (Zepf & Koo 1989; Burkey et al. 1994; Carlberg et al. 1994) suggesting that merging has possibly an important role in galaxy evolution. This is verified, for example, by the excess of blue star-forming galaxies at intermediate redshifts (Butcher & Oemler 1984). However, most of the previous works are limited to small samples of objects covering a small area in the sky and making their statistics not ideal. There are a few samples of objectively selected nearby pairs and groups of galaxies (Karachentsev 1972; Hickson 1982; Maia et al. 1994; Prandoni et al. 1994; Soares et al. 1995; Reduzzi & Rampazzo 1995). On the other hand, intermediate redshifts lacks of such extensive survey since this type of survey requires large telescopes equipped with modern CCD detectors. Therefore, the number of faint galaxies with known redshift is still low (see Koo & Kron 1992 and Ellis 1995 for reviews on redshift surveys and imaging of the faint galaxy population; Carlberg et al. 1994; Yee & Ellingson 1995). We have started a long term project in order to improve this situation. In this paper, we present an extensive catalog of faint interacting galaxies in pairs and groups. We believe that catalogs like these are one of the first steps towards understanding galaxy evolution. A following step will be to measure redshifts for a statistically significant number of galaxies which will require a large amount of observing time at 4-m class telescopes. However, our sample is equatorial and accessible from both hemispheres.

2. Observations and Reductions

The observations were taken at the CTIO 4m prime focus camera by the High-Z Supernovae Search Group with a redshifted filter B which is almost equivalent to a regular Kron-Cousin R filter (B/($z = 0.4$)). The image set comprises of 46 equatorial images of $15' \times 15'$ ($0.44''$ pixel^{-1}) making a total area of 2.8532 deg^2. Single 5 minutes exposures were sufficient to provide good quality images.

To convert instrumental magnitude into m$_R$ we used the equation m$_R$= 31.5 - 2.5log(counts) - 0.1X, where X is the airmass. The photometric zero point was calibrated by observing a m$_R$=16.97 star at R.A.=10^h 50^m 49^s and DEC.= -9°14′31.4″ (epoch 2000), with the AAT and the MSSSO 2.3m on two photometric nights (Schmidt 1995).

The CCD images were first convolved with a lowered Gaussian kernel and then images were detected by using a local maximum technique. The arrays were background subtracted to have zero mean (i.e., local sky has already been subtracted), and smoothed or cross-correlated. There are two conditions which must be satisfied, the intensity of the pixel must be above a predetermined threshold (1.5σ) and that the pixel must be a local maximum. The algorithm then combines all local maxima within N contiguous pixels of each other and compute centroids of each final local maximum. Finally, objects which are closer to each other than a given tolerance are merged. Masks were made to exclude zones with bright objects and bad pixels. A total area of 0.2372 deg^2 was excluded.

The photometry was performed by an algorithm which measures the "total" light within a variable aperture (Kron 1980; Infante 1987) which is better for extended objects than fixed circular apertures. Objects were then classified as galaxies, stars or noise by using the properties of the inverse first and second moments of the images which gives a measure of intrinsic size and central compactness, respectively.

3. Completeness

Simulations were performed in order to test detection and photometry of faint images as a function of magnitude for different types of data - that is to say, different observing conditions and object type (i.e., stars, disk galaxies and spheroidal galaxies). These simulations were carried out in the same way as in Infante (1987). Stars and galaxies were simulated on top of flat noisy frames and then detection and photometry routines were run. The tests were designed so that the simulations resemble as much as possible the data described above. (For more details see Infante 1987).

The noise frames (500 pixels) were created to have the same characteristics as the real frames. These were as follows: pixel size = $0.44''$, sky background = 4100 DU, noise = 40 DU/pixel, FWHM = $2''$, read-out-noise = 4.2 [e], gain = 2.9 [e/DU]. The pixel values of the noise frames were drawn from a gaussian distribution; the noise being the dispersion and the sky background being the mean. Stars, disk galaxies and spheroidal galaxies were simulated in turn. 50 paired objects of the same class, with the same parameters, were created at random positions on the noise frames. The detection and photometry algorithms were then run. The variables were the magnitude ($20 \leq m_R \leq 24$), the seeing ($1'' \leq seeing \leq 1.6''$) and the pair separation ($1'' \leq \theta \leq 6''$). The redshift determines the angular size of the galaxies through the relativistic angular size-distance relation.

3.1. Limiting Magnitude

The detection results for stars and spheroidal galaxies are shown in Fig. 1. In all cases, this magnitude is a function of sky surface brightness. However, for our data it spans less than 0.2 magnitudes in m_R. For unresolved objects (FWHM$< 1.3''$) the completeness limit is $m_R \approx 23.0$ at $\mu_{m_R} \approx 20.7$, which is the case for the bulk of our observations. The limiting magnitude for resolved objects depends on the surface brightness of the object. For a fixed magnitude the surface brightness goes down with diameter, hence distance. Thus, the limiting magnitude for galaxies is a function of redshift. For both, disk and spheroidal galaxies, at $z \leq 0.3$, the 99% completeness limit is $m_R \approx 22.8$ for $\mu_{m_R} \approx 20.7$, very close to what we obtained for stars.

The turn over of galaxy number counts as a function of magnitude provides a rough estimate of completeness as well. It is well known that galaxy number counts in R rises as dlogN/dm ≈ 0.3 up to $R < 25$ (Infante et al. 1986). Any turn over in the number counts at $R < 25$ must be due to incompleteness. Galaxy number counts as a function of m_R are shown in Fig. 2. The slope of the counts is d(logN)/dm = 0.33 in agreement with Infante et al. (1986). It is clear from this figure that the turn over in the number counts occurs at $m_R > 22.5$. We, therefore, claim that our catalog of pairs and groups is 99% complete at $m_R < 22$.

3.2. Separation

We now turn to determine the limit at which our finding algorithm is able to resolve galaxies separated by a given angular distance. For each simulation, on a 500×500 noise frame, 50 pairs of objects (resolved and unresolved) were placed at random positions. The variables were the seeing and the angular separation. Simulations were carried out for m_R=20 and m_R=22 in order to detect any brightness dependence. After 50 runs we conclude that both objects in pairs separated by more than $2''$ are always detected for $1.0'' \leq seeing \leq 1.6''$. This limit does not change significantly with brightness, for unresolved (stars) and for resolved (spheroidal galaxies) objects.

4. Selection Criteria

Our selection criteria are based on separations between pairs of galaxies. Pairs of faint galaxies (separation $\Delta\theta$) are chosen such that $\theta_{min} < \Delta\theta < \theta_{max}$. Here θ_{min} is the minimum separation at which pairs can be reliably separated (nominally $2''$); θ_{max} corresponds to a physical separation, r_p, chosen so that: (*i*) physical pairs are doomed to merge in $< 10^9$yr (on the basis of both empirical studies and conventional dynamics); and (*ii*) most pairs in the sample are physically associated. These conditions are satisfied by $r_p \approx 30$ kpc, which corresponds to $\approx 10''$ at $z = 0.3$, assumed to be the mean redshift of galaxies in our sample; e.g., the Supernova 1995K was found at $z = 0.478$ (Leibundgut et al. 1995).

We have used selection criteria based on those of local samples (Karachentsev 1972; Hickson 1982; Prandoni et al. 1994) in order to define our isolation criterion and to avoid unrelated galaxies, i.e., optical pairs (Sulentic 1992). We defined the radius, R_G, which is the radius of the smallest circle containing the centers of the group members (for pairs, R_G is half of the pairs separation). We selected only pairs and groups with no neighbors within a distance R_N to the center of the group, so that $R_N/R_G \geq 3$.

Our group algorithm selects pairs and groups of galaxies within $19 < m_R < 22$ and $2'' < \theta < 6''$. However, because of our completeness limit (see §3.1) we can only identify galaxies that are brighter than $m_R = 22$. Therefore, groups and pairs which have neighbors fainter than this limit were still considered as isolated. Compactness constraint like the one defined by Prandoni et al. were not used in our group selection since this constraint is less stringent at faint magnitudes (see Fig. 6 in Prandoni et al. 1994). The main difference between our criteria and local samples criteria resides in the fact that our membership criterion considers all galaxies within the range of magnitude $19 < m_R < 22$ instead of considering all galaxies up to three magnitudes fainter than the brightest member.

All pairs and groups selected were inspected by eye and classified according to their components intensities and isolation. We centered each pair and group in a $14''$ rectangular region and used a surface plot centered on the objects to measure their intensities, I (see §6 for classification). 75 pairs and

1 group were identified as spurious detections and removed from the catalog. We have also excluded 0.3942 deg^2 due to fields overlapping. Only galaxies within $19 < m_R < 22$ were considered and, therefore, galaxies outside this limit but which fell inside the isolation circle were not considered as members and the group was still selected. When we classified our pairs/groups we looked for these objects (see column 10 of Tables 1 and 2). Pairs/groups classified as *4* are pairs/groups with a faint object very close or with a bright object on the border of a 14″ box; pairs/groups with an object within a 14″ box were classified as *5*. Approximately half of the quartets belongs to these classes.

5. Positions

The following procedure is used to transform positions, (x, y), on the CCD images to equatorial coordinates (α, δ) for the equinox 2000.0. A number of faint stars that are visible in our fields were chosen from the Digitized Sky Survey images. An average of 20 stars were matched to the CCD positions and were used to find the coefficients of second-order polynomials of the following form:

$$\alpha - \alpha_o = \sum_{j=1}^{m} \sum_{i=1}^{j} a_{ij} (x - x_o)^{j-i} (y - y_o)^{i-1} \ , \qquad (1)$$

$$\delta - \delta_o = \sum_{j=1}^{m} \sum_{i=1}^{j} b_{ij} (x - x_o)^{j-i} (y - y_o)^{i-1} \ . \qquad (2)$$

where $(x - x_o)$, $(y - y_o)$ are the CCD centroid coordinates from a reference position, and $(\alpha - \alpha_o)$, $(\delta - \delta_o)$ are equatorial coordinates relative to the reference coordinates. A total of 12 independent coefficients defines the transformation from machine (x, y) units to equatorial, (α, δ). The accuracy of the fit (as judged by the root mean square residuals of the fit) was better than 0.5″.

6. Description of the Catalogs

In Tables 1 and 2 we present the catalogs of faint pairs and groups of galaxies. The catalog contains information on all of the objects that are outside the "excised areas" discussed in §2. Five parameters per object are stored. The column entries are described below.

Columns (1) to (6). Right ascension (α) and declination (δ), epoch 2000.

Column (7) The "total" m_R magnitude as defined in §2, calibrated as described in §3.

Column (8) Group Radius, R_G, in arcsecs as defined in §4. For pairs, R_G means half of the pairs separation.

Column (9) Isolation parameter, R_N/R_G, as defined in §4. All pairs and groups were selected such that $R_N/R_G > 3$.

Column (10) Pairs and Groups Classification: 1- members with similar intensity ($I_{min} \approx I_{max}$) and with no other object within a 14″ box; 2- members with $I_{min} > 0.5\, I_{max}$ and with no other object within a 14″ box; 3- members with $I_{min} \leq 0.5\, I_{max}$ and with no other object within a 14″ box; 4- pairs or groups with a faint object very close or with a bright object on the border of a 14″ box; 5- pairs or groups with an object within a 14″ box; 6- pairs with a faint member which could be an HII region of brighter galaxy. I_{min} and I_{max} correspond to members with minimum and maximum intensity; a 14″ box was centered in each pair or group (see §4).

7. Discussion

We have found 1751 isolated pairs of galaxies and 30 groups of galaxies within $19 < m_R < 22$ and $2'' < \theta < 6''$ out of 73,988 galaxies in a total area of 2.2333 deg^2. We have performed a simulation in order to compare the number of pairs and groups identified by our algorithm with the number predicted by galaxies randomly distributed on the sky. Our simulation makes a random sample with all the galaxies identified within the 2.616 deg^2 area,which corresponds to the total area (2.8532 deg^2) subtracted of the masked area (0.2372 deg^2). The same pair and group selection criteria described above was applied to the random sample.

The pair radius, R_G (half the pair separation), and the nearest neighbor index, R_N/R_G, histograms are presented in Figures 3 and 4. The dotted line in both histograms represents detections on the random catalogs and the data used are for the 2.616 deg^2 area. Our results show clearly an increase in pairs and groups of galaxies in comparison to the randomly generated catalog. For instance, at $3'' < \theta < 4''$ there are 2 to 3 times more pairs as expected from the random catalog, which in turn, is an excess of close pairs over what would be expected from an extrapolation of $\omega(\theta)$

at larger θ (Carlberg et al. 1994; Infante & Pritchet 1995). Future papers will discuss the interpretation of these results in order to examine the rise in the merger rate with redshift (Infante et al. 1996) and a second catalog covering a different area in the sky has been selected (de Mello et al. 1996). The authors hope that this work and the fact that these objects are equatorial and accessible from both hemispheres will motivate an effort to obtain redshifts for many objects in these catalogs.

We are grateful to the High-Z Supernovae Search Group for making their images available, to the anonymous referee for helpful comments, to C. Mendes de Oliveira for interesting suggestions, and to Gladys Vieira for the careful work in obtaining the coordinates. We acknowledge the Digitized Sky Survey produced at the Space Telescope Science Institute under U. S. Government grant NAG W-2166. DFM thanks FAPESP and CNPq for the fellowships and the hospitality of CTIO and P. Universidad Católica. LI thanks Fondecyt Chile for support through 'Proyecto 1930570'.

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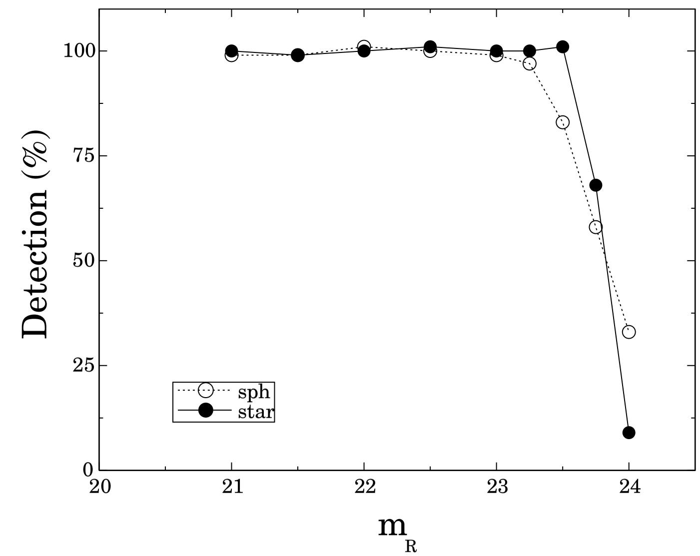
Fig. 1.— Percentage of objects (resolved and unresolved) detected as a function of magnitude m_R. Filled circles are stars and open circles are spheroidal galaxies.

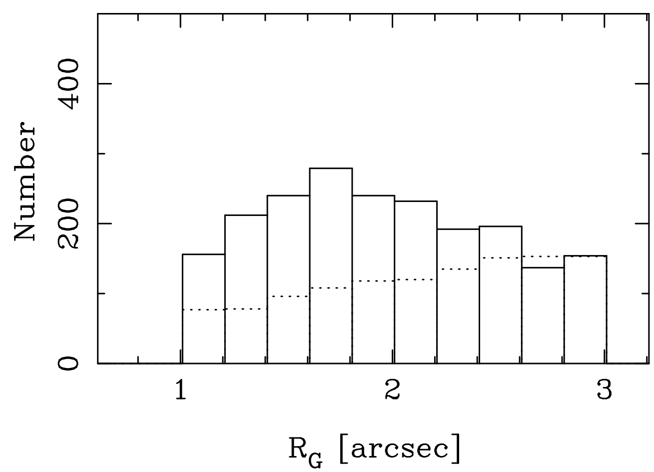
Fig. 2.— Galaxy number counts as a function of m_R magnitude. The poisson error bars are smaller than the symbols in most points. The turn over in the number counts is due to incompleteness.

Fig. 3.— Histogram of the group radius, R_G, for pairs. The survey data are shown as a solid line and the random catalog as a dotted line. (See the text for details.) Note that for pairs R_G corresponds to half the pair separation.

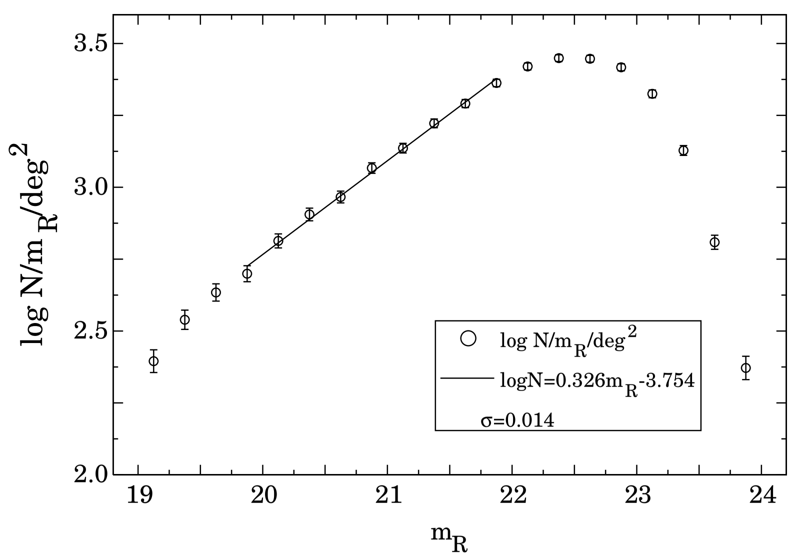
Fig. 4.— Histogram of the isolation parameter, R_N/R_G, for pairs. The survey data are shown as a solid line and the random catalog as a dashed line. (See the text for details.) Pairs and groups with $R_N/R_G < 3$ are excluded from the catalog.



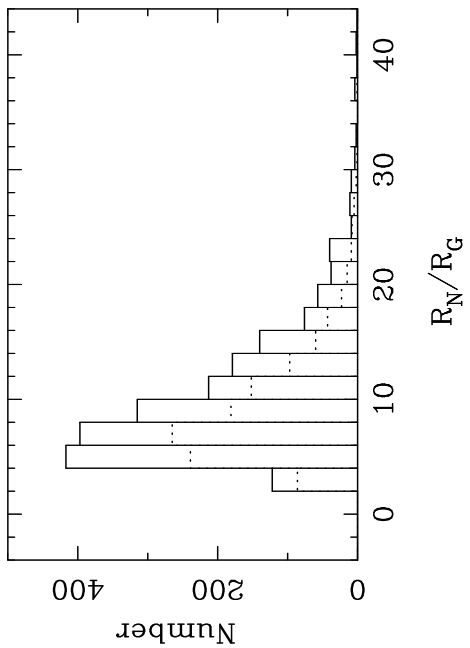
Detection (%)
sph
star
m_R



Number
R_G [arcsec]



log N/m_R/deg^2
logN=0.326m_R-3.754
σ=0.014
m_R


Number
0
200
400
0
10
20
30
40
R_N/R_G