COMPARATIVE STUDY OF ASYMMETRY ORIGIN OF GALAXIES IN DIFFERENT ENVIRONMENTS. II.
NEAR-INFRARED OBSERVATIONS

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ABSTRACT
In this second paper of two analyses, we present near-infrared (NIR) morphological and asymmetry studies performed in a sample of 92 galaxies found in different density environments: galaxies in compact groups (CGs; HCGs in the Hickson Catalog of Compact Groups of Galaxies), isolated pairs of galaxies (KPGs in Karachentsev’s list of isolated pairs of galaxies), and isolated galaxies (KIGs in Karachentseva’s Catalog of Isolated Galaxies). Both studies have proved useful for identifying the effect of interactions on galaxies. In the NIR, the properties of the galaxies in HCGs, KPGs, and KIGs are more similar than they are in the optical. This is because the NIR band traces the older stellar populations, which formed earlier and are more relaxed than the younger populations. However, we found asymmetries related to interactions in both KPG and HCG samples. In HCGs, the fraction of asymmetric galaxies is even higher than what we found in the optical. In the KPGs the interactions look like very recent events, while in the HCGs galaxies are more morphologically evolved and show properties suggesting they suffered more frequent interactions. The key difference seems to be the absence of star formation in the HCGs; while interactions produce intense star formation in the KPGs, we do not see this effect in the HCGs. This is consistent with the dry merger hypothesis; the interaction between galaxies in CGs is happening without the presence of gas. If the gas was spent in stellar formation (to build the bulge of the numerous early-type galaxies), then the HCGs possibly started interacting sometime before the KPGs. On the other hand, the dry interaction condition in CGs suggests that the galaxies are on merging orbits, and consequently such system cannot be that much older either. Cosmologically speaking, the difference in formation time between pairs of galaxies and CGs may be relatively small. The two phenomena are typical of the formation of structures in low-density environments. Their formation represents relatively recent events.

Key words: galaxies: interactions – galaxies: photometry – galaxies: structure

Online-only material: figure set

1. INTRODUCTION
This paper presents the second of two analyses about the importance of environment on the formation and evolution of galaxies observed in the nearby universe. In the first paper (Plauchu-Frayn & Coziol 2010, hereafter Paper I), we have presented the results of our morphological and asymmetry study in the optical (V and I filters) for a sample of 214 galaxies found in three different density environments: galaxies in compact groups (CGs; HCGs, Hickson 1982), isolated pairs of galaxies (KPGs, Karachentsev 1972), and isolated galaxies (KIGs,Karachentsev 1973). We have also performed a comparative statistical analysis of the isophotal and asymmetry properties of these galaxies.

In the optical, we observed some clear differences in the properties of galaxies in the different environments. First, isolated galaxies tend to be more compact and symmetrical than galaxies in pairs or in CGs. This suggests that interactions produce stellar orbits with higher energies. Second, evidence for interactions seems more obvious for galaxies in pairs than for galaxies in CGs. Because the HCGs are richer in early-type galaxies than in the KPGs, these differences suggest that interactions played a more important role in the CGs in the past either because the high-density environment of CGs favors more interactions and consequently the galaxies evolve more rapidly in such systems, or because galaxies in CGs started interacting earlier in the past than those in pairs.

This paper extends our morphological and asymmetry study to the near-infrared (NIR) using deep J and K′ images. Contrary to the optical, the NIR bands are sensitive to the older, less massive but dominant stellar populations and trace the distribution of the mass of galaxies better (Frogel et al. 1978). Consequently, using NIR images allows us to compare interaction effects over different timescales than in the optical. This is important in CGs where it is suspected that galaxies interact and merge under dry conditions (Coziol & Plauchu-Frayn 2007).

Our analysis is similar to the one used in the optical (Plauchu-Frayn & Coziol 2010, hereafter Paper I). We have independently applied two different methods: fitting of ellipses on the isophotal levels of the galaxies and determination of their asymmetry levels. In Section 2, we present the properties and selection of the sub-samples observed in the NIR; in Section 3, we describe the conditions of observations and explain the reduction process; in Section 4, we present the results of our photometry and asymmetry analyses, and the comparative statistical studies in different environments; in Section 5, we compare the level of nuclear activity star formation or active galactic nuclei (AGNs) in the different environments using spectra extracted from the Sloan Digital Sky Survey (SDSS); in Section 6, we discuss our results, comparing them with those obtained in the optical; and our conclusions are stated in Section 7.
2. SELECTION AND PROPERTIES OF THE OBSERVED GALAXIES

The sub-sample for our NIR analysis consists of 92 galaxies taken from our list of galaxies previously observed in the optical. A detailed description of the properties of these galaxies can be found in Paper I. Only 21 galaxies were part of our previous NIR analysis (Coziol & Plauuch-Frayn 2007). The remaining 71 galaxies are from new observations.

The galaxies observed in the NIR form only 50% of those observed in the optical. This is because observations in the NIR are more complicated and time expensive than in the optical. In particular, in the NIR, one has to constantly move the telescope forming a mosaic sequence. This technique is used to avoid ghost images (remnants of galaxy images appear on the pixels if the target is kept at the same position) and to allow proper sky subtraction. In setting up our sub-sample, therefore, a supplementary step consisted of selecting galaxies with a semimajor axis in the range $15^\prime \leq a \leq 90^\prime$, to allow the telescope to move in a cross or a square pattern.

The properties of the galaxies observed are reported in Table 1 for the KIGs, Table 2 for the KPGs, and Table 3 for the HCGs. As explained in Paper I, morphological types for the KIG sample were taken from Sulentic et al. (2006). For the KPG and HCG samples, these were determined based on our own CCD images. Evidence for bars was added based on the optical images and/or our isophotal study. No new bars were added based on the NIR images.

In Figure 1, we compare the properties of the observed samples in the NIR with the properties of the galaxies in their respective catalogs. The $B$ and $K_s$ magnitudes (Paturel et al. 1994, 1997; Jarrett et al. 2000) and the revised numerical code of the morphological type (de Vaucouleurs et al. 1991) were taken from the HyperLeda\(^2\) and Two Micron All Sky Survey (2MASS)\(^3\) databases. Also, in Table 4 we compare the diameters in both magnitudes and the redshifts, as found in the HyperLeda and 2MASS databases. One can see that the observed samples are fairly representative of their parent samples. In Table 4, the results of the Mann–Whitney statistical tests are consistent with no difference in absolute magnitude for the observed KPGs.

In the case of the KIGs, the observed sample is slightly more luminous than in the whole catalog. This is because they are located slightly nearer than the galaxies in the whole catalog. The HCGs are also brighter and bigger in the observed sample than in the whole catalog. These differences are a consequence of the criteria used in preparing the NIR observations and will be taken into account during our analysis.

\(^{2}\) HyperLeda database: http://leda.univ-lyon1.fr

\(^{3}\) http://irsa.ipac.caltech.edu
3. OBSERVATION AND REDUCTION

We have obtained new NIR images in the $J$ (1.28 $\mu$m) and $K'$ (2.12 $\mu$m) bands for 71 galaxies with the 2.1 m telescope of the Observatorio Astronómico Nacional, located in the Sierra San Pedro Mártir, in Baja California, Mexico. Five different runs were necessary (Table 5). The instrument used was CAMILA (Cruz-González et al. 1994). This camera is formed of four NICMOS3 detectors with $256 \times 256$ pixels, which are sensitive over the range 1–2.5 $\mu$m. This instrument includes a diaphragm with a wheel of filters, which are cooled to reduce the background radiation level. The optical system, which consists of a mirror and a focal reducer designed for the $f/4.5$ secondary, gives a $3.6 \times 3.6$ field of view, corresponding to a plate scale of 0.85 pixel$^{-1}$.

Because the detector in the NIR saturates rapidly (due to the brightness of the sky), several short exposures were obtained and combined to form one final image. For each filter, we have used the longest integration time possible that keeps the total counts within the linear range of the detector response. For the $J$ filter, we took for each galaxy $\sim 40$ images of 80 s. For the $K'$ filter, we took $\sim 80$ images of $\sim 15$ s.

As mentioned in the previous section, a mosaic technique was used in order to map and properly sample the quickly varying sky background. The technique consists of moving the telescope between each short exposure. The way the telescope moves depends on the angular size of the target galaxy. Usually we form a cross or a square, but sometimes we must alternate between the target and the sky when the object covers the whole detector (for example, the whole CG). In general, the combination of a sequence of mosaic images yields a total integration time which is equal to or below the observation time. This is due to the rejection of some bad images in a sequence. In Tables 1–3, Columns 6 and 7 list the final total exposure time in the $J$ and $K'$ bands, respectively. Note that to increase the signal-to-noise ratio (S/N) and/or to replace bad images, many galaxies were observed for more than one night, but only during the same observing run.

The nights were clear and photometric. Usually, and as expected for the NIR, the observations are not affected on full moon nights. However, in a few cases where the moonlight was reflected by the dome we have discarded the images.

For photometry calibration, several standard stars were observed during each observing run. These stars were taken from the UKIRT4 (Hawarden et al. 2001) extended standards list.

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**Table 3**

Properties of the Observed HCG Galaxies

| Name     | R.A. (J2000) | Decl. (J2000) | $v_{\text{vir}}$ (km s$^{-1}$) | Morph. | $l_2$ | $t_3$ |
|----------|--------------|--------------|-------------------------------|--------|------|------|
| HCG 10a  | 01 26 21     | 34 42 10     | 5269 SBb                      |        |      |      |
| HCG 37a* | 09 13 39     | 29 59 35     | 6844 E                       |        |      |      |
| HCG 37b* | 15 19 24     | 29 59 35     | 6840 Sb                      |        |      |      |
| HCG 40a* | 09 38 53     | -04 50 56    | 6751 E                       |        |      |      |
| HCG 40b* | 09 38 54     | -04 51 56    | 6785 S0                      |        |      |      |
| HCG 40c* | 09 38 53     | -04 51 37    | 6833 Sb                      |        |      |      |
| HCG 40d* | 09 38 55     | -04 50 16    | 6435 Sba                     |        |      |      |
| HCG 40e* | 09 38 55     | -04 51 29    | 6568 Sb                      |        |      |      |

**Notes.** Columns: (1) catalog galaxy identification; (2) right ascension from HyperLeda (J2000); (3) declination from HyperLeda (J2000); (4) radial velocity from Hickson et al. (1992) corrected for infall of Local Group toward Virgo; (5) morphological type as determined in this work; (6) and (7) total exposure time in the $J$ and $K'$ bands, respectively.

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**Table 4**

Properties of Observed Versus Catalog Galaxies

| Sample | $M_B$ (mag) | $P_{\text{MW}}$ | $M_{K_s}$ (mag) | $P_{\text{MW}}$ | $D_B$ (kpc) | $P_{\text{MW}}$ | $D_K$ (kpc) | $P_{\text{MW}}$ | $V_{\text{vir}}$ (km s$^{-1}$) | $P_{\text{MW}}$ |
|--------|-------------|----------------|----------------|----------------|-------------|----------------|-------------|----------------|----------------------------|-------------|
| KIG    | -20.60/-20.30 | 0.007           | -23.65/-23.27 | 0.036           | 27/22      | 0.091         | 18/16      | 0.088          | 5034/6296              | 0.0161      |
| KPG    | -20.36/-20.32 | 0.266           | -23.55/-23.89 | 0.122           | 25/23      | 0.465         | 18/16      | 0.350          | 4942/6326              | 0.2218      |
| HCG    | -20.57/-20.01 | 0.001           | -24.60/-23.60 | 0.002           | 31/24      | 0.001         | 23/16      | 0.001          | 6783/7970              | 0.2295      |

**Notes.** Columns: (1) sample identification; (2) median absolute magnitude in $B$, $M_B$, of observed/catalog galaxies; (3) probability $P$ for $M_B$; (4) median absolute magnitude in $K_s$, $M_{K_s}$, of observed/catalog galaxies; (5) probability $P$ for $M_{K_s}$; (6) median diameter in the optical, $D_B$, of observed/catalog galaxies; (7) probability $P$ for $D_B$; (8) median diameter in the NIR $D_K$ of the observed/catalog galaxies; (9) probability $P$ for $D_K$; (10) median redshift, $v_{\text{vir}}$, of observed/catalog galaxies; and (11) probability $P$ for $v_{\text{vir}}$. Values were obtained from Mann–Whitney tests; underlined values indicate significant differences between the samples.

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4 The United Kingdom Infrared Telescope is operated by the Joint Astronomy Centre on behalf of the Science and Technology Facilities Council of the UK.
Figure 1. Distribution of catalog vs. observed galaxies: (a) KIG, (b) KPG, and (c) HCG.

### Table 5

| Run | Date    | Filters | Seeing (FWHM) | \(\sigma_J\) (mag) | \(\sigma_K'\) (mag) |
|-----|---------|---------|---------------|---------------------|--------------------|
| 1   | 2006 Aug| J, K'   | 1.2 ″        | ±0.17               | ±0.08              |
| 2   | 2007 May| J, K'   | 2.2 ″        | ±0.08               | ±0.04              |
| 3   | 2007 Sep| J, K'   | 1.8 ″        | ±0.06               | ±0.09              |
| 4   | 2008 May| J, K'   | 1.4 ″        | ±0.02               | ±0.03              |
| 5   | 2008 Jul| J, K'   | 1.4 ″        | ±0.02               | ±0.08              |

**Notes.** Columns: (1) running number, (2) observation date, (3) average FWHM measured on standard stars used for focus, (4) filters, (5) and (6) calibration uncertainties for the \(J\) and \(K'\) bands, respectively.

available at the Web site of the observatory.\(^5\) The instrumental magnitudes for the standard stars were estimated by measuring the flux of each observed star after correcting for the atmospheric extinction. The calibration equations were calculated by fitting linear regressions on the observed values. For the photometric error, we adopted the standard deviation between our estimated magnitude and the magnitude determined in the UKIRT standards list. Magnitudes for the observed galaxies have also been corrected for galactic extinction (Schlegel et al. 1998). Because the galaxies observed are at \(z \leq 0.04\), no \(K\)-correction has been applied. Details for the observations are given in Table 5. The calibration in flux was applied only after the different analyses (isophotal and asymmetry) were performed. This way of doing keeps the \(S/N\) in the different images as high as possible.

The reduction and calibration processes were standard and within the Image Analysis and Reduction Facility (IRAF).\(^6\) One useful characteristic of CAMILA is that it subtracts a bias image from the target image after each exposure. This reduction step was consequently not needed. The next step consisted of trimming the individual images. This is done to remove the various bad lines and columns at the edges of the detector and to eliminate the effect due to vignetting. We subsequently applied a mask on all the images to remove the bad pixels. Normalized sky flats in each filter were used to correct for the differences in quantum response. These normalized flats were obtained by fitting a two-dimensional surface (with IMSURFIT) on combined sky flats.

In the NIR, one important step of the reduction process is to eliminate the sky contribution. To do so, we formed a median sky image by combining four adjacent exposures in the mosaic sequence and subtracted it from the corresponding exposure in the sequence. After aligning and trimming the images, the sequence of exposures was combined. First, the \((x, y)\) coordinates of the target in each image were measured using the circular aperture photometry option. These positions were used to determine the optimal shift needed to put the target in the different frames at exactly the same position, keeping the field of view as large as possible. These shifts were on the order of a tenth of a pixel. After shifting, we trimmed the individual images to the most optimum size. Before combining the exposures, most of the cosmic rays were removed using the COSMICRAYS task. In some cases, it was necessary to remove the remaining cosmic rays by hand by using the IMEDIT task. An average image was then formed by combining the whole sequence of exposures.

### 4. RESULTS OF ANALYSIS

It is known that during interactions some of the properties of galaxies are affected. Properties such as morphology, brightness, color, and nuclear activity are changed as a result of the disruption of gas and stellar component during the encounter (Larson & Tinsley 1978; Kennicutt & Keel 1984; Lui & Kennicutt 1995; Laurikainen & Salo 2000; Patton et al. 2005; Woods & Geller 2007; McIntosh et al. 2008).

To further study this, for each galaxy two different analyses were performed: fitting of ellipses on the NIR isophotes and estimation of the level of asymmetry. The application of these

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\(^5\) [http://www.astrossp.unam.mx/estandar/standards/fs_extended.html](http://www.astrossp.unam.mx/estandar/standards/fs_extended.html)

\(^6\) IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
methods is similar to that used in the optical. A detailed explanation of the methods can be found in Paper I. For the sake of homogeneity, the analysis of the 21 HCG galaxies previously observed by Coziol & Plauchu-Frayn (2007) was completely redone. The results of our analysis are reported for individual galaxies in Tables 6, 7, and 8 for galaxies in KIG, KPG, and HCG samples, respectively.

By measuring these parameters at the inner and outer parts in the observed galaxies, we plan to study the effect of interactions on galaxies in the three different environments. To do this, we have chosen $r_0$ to be a radius independent of the distribution of light inside and outside of which we will measure isophotal parameters, following the methods described in Paper I. Using the major axis at 20 mag arcsec$^{-2}$ in the $K_2$ band (Jarrett et al. 2000) as given in 2MASS, we have determined the linear diameters in kiloparsecs, $D_{K_2}$, for galaxies in the HCG, KPG, and KIG catalogs and determined the median of the diameters’ distribution. The median value obtained is 14 kpc. In our sample, a few galaxies (22% of the sample: eight HCGs, nine KPGs, and three KIGs) turned out to have a $D_{K_2}$ which is smaller than this value. Consequently, we have used two different $r_0$, equal to 3.5 kpc (approximately $D_{K_2}/4$) for the normal sized galaxies (approximately $M_J < -22$) and half this value, 1.8 kpc, for the galaxies with smaller diameters ($M_J > -22$).

Based on the surface brightness profiles, $\mu(r)$, of the galaxies, we have estimated the concentration index, $C$. This is defined as (Paper I) $C_{<r_0} = \mu_{r_0} - \mu_{<r_0}$ and $C_{>r_0} = \mu_{>r_0} - \mu_{r_0}$ inside and outside $r_0$, respectively. $C$ is a measure of the light concentration of a galaxy profile having high values for centrally concentrated light profiles. Early-type galaxies tend to have the most concentrated light profiles, while late-type galaxies have the least concentrated ones (Abraham et al. 1994; Shimasaku et al. 2001). On the other hand, interactions are expected to perturb the stellar material, changing light profiles of galaxies in the process and affecting their concentration indices.

Finally, to make our interpretation of the asymmetry study more straightforward, we have used a slightly different measure of asymmetry than that found in the literature (Schade et al. 1995; Conselice et al. 2000; Hutchings & Proulx 2008). The level of asymmetry as a function of the semimajor axis $a$ is estimated by the following formula:

$$A(a)_{180} = \frac{I_0}{I_{180}},$$

(1)

where $I(a_0)$ is the intensity in the original image and $I(a)_{180}$ is the intensity in the rotated image. This formula yields values between 1 (completely symmetric) and $>1$ (completely asymmetric). We refer the reader to Paper I for a detailed description of this method.

In Figure 2, we show, as an example, the mosaic for one very asymmetric galaxy (the full sample of mosaic images is available in the online version of the journal). In the left panel of Figure 2, we present the isophotal parameter profiles. The dashed vertical line marks the location of the half-radius, $r_0$, adopted. In the right panel of the same figure, we present the $J$-band image (or the $K'$-band image for galaxies that were observed only in this filter) displayed on a logarithmic scale. We also present the residual image from the asymmetry analysis (bottom left image). In all these images, north is at the top and east is to the left.
Figure 2. KPG 313B mosaic. Left panel: isophotal parameter profiles as a function of the semimajor axis $a$—from top to bottom: surface brightness in $J$ and $K'$ (mag arcsec$^{-2}$), $J - K'$ color index (magnitude), ellipticity, position angle (degrees), isophotal deviation from pure ellipse, and asymmetry level. The dashed vertical line indicates the average half-radius $r_0 = 3.5$ kpc (or $r_0 = 1.8$ kpc when indicated). Right panel: the $J$-band image displayed on a logarithmic scale and the residual image (bottom image). North is up and east is to the left.

(The complete figure set (92 images) is available in the online journal)

4.1. Comparison of Galaxies with Same Morphologies in Different Environments

We have divided our samples into three morphology groups: early type (E–S0), intermediate type (Sa–Sb), and late type (SbcIm). The median values of the properties measured on the observed galaxies in the three different groups are reported in Tables 9, 10, and 11 for early, intermediate, and late types, respectively. We now discuss the variations on the properties encountered for each group depending on their environment. To check for the statistical significance of the observed variations, non-parametrical tests (Kruskal–Wallis for three samples or Mann–Whitney in the case of only two samples) were also performed. All the tests were done at a level of significance of 95%, which is the standard for these kinds of tests. The results for the statistical tests are reported in Tables 9–11.

4.1.1. Early-type (E–S0) Galaxies

We present the variations of the isophotal parameters internal to $r_0$ in Figure 3 and external to $r_0$ in Figure 4. In each graph, the $x$-axis corresponds to the $J$-band absolute magnitude of the
galaxies as estimated inside $r_0$. One observes a higher number of small-mass galaxies in the HCG than in the other two samples.

In this morphology group, only two galaxies belong to the KIGs. We have discarded them from our statistical tests. The only statistically significant differences encountered are that the HCGs tend to be less concentrated and have lower surface brightness inside $r_0$ than the KPG galaxies (see Table 9). This seems consistent with what we observed in the optical. However, since here we are observing in the NIR, the interpretation in terms of mass distribution is clearer. It seems that the orbits of the stars have higher energy in the HCGs than in the KPGs. In Paper I, we suggest that this effect was due to interactions. Thus, this difference would suggest more interactions in the HCGs than in the KPGs.

For all the other parameters, we found no statistically significant differences (see Table 9). In general, we observe less differences in the NIR than in the optical. Note, however, that some galaxies in the HCG and KPG samples are slightly more asymmetric than in the KIG one (see the bottom panel in Figure 4).

As a product of the isophotal study, we have determined the isophotal shape $a_r$ and twist $\theta$ of the early-type galaxies. In Figure 5, we see that most of the galaxies present disky isophotes ($a_r > 0$): 19 out of 23 (83\%) for the HCGs and 4 out of 9 (44\%) for the KPGs. This confirms the trends observed in the optical. The fractions of disky galaxies are also consistent with what we found in the optical.

Also consistent with the optical, we found the ellipticity in these galaxies to be quite high. In Figure 6, we show the twists as a function of the absolute magnitudes in the $J$ band. The fraction of galaxies with large twists is in agreement with that found in the optical: 57\% (13/23) of the HCGs, with a median $\theta$ value of 22°, and 33\% (3/9) of the KPGs, with a median $\theta$ value of 21°.

### Table 8

| Name   | $<r_0$ | $>r_0$ | $<r_0$ | $>r_0$ | $<r_0$ | $>r_0$ | Asymmetry |
|--------|--------|--------|--------|--------|--------|--------|-----------|
| HCG 10a | 1.0    | 1.4    | 1.0    | 1.4    |        |        | Tidal     |
| HCG 37a | 0.9    | 2.0    | 1.51   | 1.50   | 1.0    | 1.08   | Asymmetric |
| HCG 37b | 0.4    | 2.3    | 1.96   | 1.77   | 1.0    | 1.06   | Asymmetric |
| HCG 40a | 1.1    | 2.0    | 0.91   | 0.94   | 1.0    | 1.12   | Tidal     |
| HCG 40h | 1.1    | 0.3    | 0.91   | 0.91   | 1.0    | 1.00   | Symmetric |
| HCG 40c | 0.6    | 0.7    | 1.20   | 1.19   | 1.0    | 1.04   | Asymmetric |
| HCG 40d | 0.8    | 0.8    | 1.06   | 1.00   | 1.0    | 1.00   | Symmetric |
| HCG 40e | 0.3    | 0.4    | 0.85   | 0.88   | 1.0    |        | Tidal     |
| HCG 56a | 0.2    | 2.1    | 1.23   | 1.15   | 1.0    | 1.00   | Asymmetric |
| HCG 56b | 0.8    | 0.9    | 1.46   | 1.41   | 0.92   | 0.99   | Tidal     |
| HCG 56c | 0.1    | 1.0    | 1.08   | 1.09   | 1.0    | 1.00   | Bridges   |
| HCG 56d | 0.3    | 1.2    | 1.36   | 1.29   | 1.0    | 1.00   | Bridges   |
| HCG 56e | 0.4    | 1.2    | 1.12   | 0.99   | 1.0    | 1.00   | Bridges   |
| HCG 61a | 1.1    | 1.0    | 1.17   | 1.22   | 1.0    | 1.01   | Symmetric |
| HCG 61c | 0.8    | 0.9    | 1.44   | 1.40   | 1.0    | 1.05   | Asymmetric |
| HCG 61d | 1.0    | 1.0    | 0.86   | 0.86   | 1.0    | 1.00   | Symmetric |
| HCG 74a | 0.3    | 1.4    | 1.13   | 1.02   | 1.0    | 1.02   | Double nuclei |
| HCG 74b | 0.6    | 1.1    | 1.02   | 0.98   | 1.0    | 1.06   | Bridges   |
| HCG 74c | 0.7    | 0.5    | 1.00   | 0.95   | 0.96   | 1.18   | Bridges   |
| HCG 79a | 0.8    | 1.1    | 1.05   | 1.02   | 1.0    | 1.00   | Symmetric |
| HCG 79b | 0.6    | 1.3    | 1.03   | 0.90   | 1.0    | 1.03   | Tidal     |
| HCG 79c | 0.6    | 0.7    | 0.76   | 0.80   | 1.0    | 1.00   | Bridges   |
| HCG 82a | 0.7    | 1.4    | 0.76   | 0.75   | 1.0    | 1.00   | Symmetric |
| HCG 82b | 0.6    | 1.2    | 0.89   | 0.89   | 1.0    | 1.00   | Symmetric |
| HCG 82c | 0.5    | 1.3    | 1.21   | 1.21   | 1.0    | 1.00   | Tidal     |
| HCG 82d | 0.9    | 1.6    | 0.66   | 0.95   | 1.0    | 1.00   | Symmetric |
| HCG 88a | 0.7    | 0.7    | 1.18   | 1.03   | 1.0    | 1.07   | Tidal and satellite |
| HCG 88b | 0.7    | 1.1    | 0.82   | 0.82   | 1.0    | 1.00   | Symmetric |
| HCG 88c | 0.9    | 0.5    | 0.90   | 0.90   | 1.0    | 1.02   | Intrinsic |
| HCG 92b | 0.7    | 0.3    | 1.00   | 1.03   | 1.01   | 1.11   | Bridges   |
| HCG 92c | 0.6    | 1.1    | 1.27   | 1.15   | 1.0    | 1.16   | Tidal     |
| HCG 92d | 0.9    | 0.3    | 1.10   | 1.13   | 1.0    | 1.03   | Bridges   |
| HCG 93a | 1.1    | 1.6    | 1.12   | 1.00   | 1.0    | 1.00   | Symmetric |
| HCG 93b | 0.3    | 1.2    | 1.00   | 1.01   | 1.0    | 1.13   | Satellite |
| HCG 93c | 1.0    | 1.4    | 0.92   | 0.92   | 1.0    | 1.02   | Symmetric |
| HCG 93d | 1.3    | 0.9    | 1.04   | 1.23   | 1.0    | 1.00   | Symmetric |
| HCG 94a | 0.6    | 1.0    | 0.81   | 0.87   | 1.0    | 1.00   | Symmetric |
| HCG 94b | 0.6    | 1.1    | 0.80   | 1.02   | 1.0    | 1.00   | Symmetric |
| HCG 98a | 0.6    | 0.8    | 0.99   | 0.97   | 1.0    | 1.00   | Bridges   |
| HCG 98b | 1.0    | 0.5    | 0.98   | 0.96   | 1.0    | 1.14   | Bridges   |

**Notes.** Columns are the same as defined in Table 6.
Figure 3. Variations of isophotal parameters and asymmetry with environment inside the half-radius \( r_0 = 3.5 \text{ kpc} \) in early-type galaxies. For smaller galaxies (open circles), the average half-radius is \( r_0 = 1.8 \text{ kpc} \). The absolute magnitude in \( J \) is the magnitude inside \( r_0 \).

In Figure 7, we show how the isophotal parameters \( a_4 \) and twists \( \theta \) vary with the difference ellipticity \( \Delta \epsilon = \epsilon_{\text{max}} - \epsilon_{\text{min}} \). A positive value of \( \Delta \epsilon \) indicates that a galaxy is rounder in its center than at the periphery. Most of the galaxies of our samples have such a characteristic. Large values of \( \Delta \epsilon \) together with large \( a_4 \) and \( \theta \) suggest that galaxies were affected by interactions. Once again, the results are similar to those observed in the optical, while no other significant difference is observed between the HCG and the KPG samples.

4.1.2. Intermediate-type (Sa–Sb) Galaxies

In Figures 8 and 9, we show the variations of the isophotal parameters internal and external to \( r_0 \), respectively, for the Sa–Sb group. The only statistically significant differences found are that the KPG galaxies tend to be slightly redder in their centers than the HCGs and more asymmetric than the KIGs outside \( r_0 \) (see Table 10). In the optical, differences between KPGs and HCGs were not significant. The difference in color in the NIR is puzzling. This cannot be due to extinction, because then we would have expected a difference in the optical as well. Usually redder colors suggest older stellar populations. However, it may also suggest a difference in terms of star formation or AGN activity. For example, the presence of numerous supergiant stars due to a recent burst could also produce redder colors (Frogel & Elias 1987). Alternatively, it could be that the KPGs are redder because of more intense AGN activity (Kotilainen & Ward 1994) in some of these galaxies. Both effects would be consistent with interaction effects.

4.1.3. Late-type (Sbc–Im) Galaxies

In Figures 10 and 11, we show variations in the late-type galaxies of the isophotal parameters internal and external to \( r_0 \), respectively. In this morphological group, we observe much more differences than in the other two groups (Table 11). The KPGs tend to be fainter in the \( J \) band than the HCGs and KIGs. The HCGs also have slightly higher surface brightness inside \( r_0 \) and are more concentrated outside this radius than the KPGs. These differences suggest variations in stellar populations and
distributions. The lower luminosity for the KPGs and higher surface brightness for the HCGs suggest a larger number of old stars in the nucleus of HCGs than that of KPGs. The higher concentration outside the radius for the HCGs is consistent with higher energy orbits.

In this morphology group, the KPGs and HCGs are also much more asymmetric than the KIG galaxies inside $r_0$, while outside this radius the most asymmetric are the KPGs (see Table 11).

This suggests that this difference is related to interaction effects, and not due to differences in internal processes such as a bar structure, stochastic star formation propagation, or wave density.

4.2. Origin of the Asymmetries in the NIR

In general, we found less differences among NIR properties of galaxies in different environments than those observed in
the optical. This is as expected based on the sensitivity of the different filter bands to different stellar populations. The NIR follows the distribution of the less massive, but dominant, stellar populations. Since these stars formed earlier, we expect that their spatial distribution has already reached some sort of equilibrium within the potential well of the galaxies, and this is independent of galaxy environment.

On the other hand, we saw that in general, and as is already observed in the optical, the level of asymmetry appears slightly higher in the KPGs and the HCGs than in the KIGs, being more obvious in the KPGs than in the HCGs. However, this phenomenon in the NIR also seems to depend on the morphology: the early- and intermediate-type galaxies are more symmetric than the late-type ones. To isolate the effect of morphology on the asymmetry, we must clearly identify the nature of the asymmetries in the NIR. Our method is similar to the one developed in the optical. It consists of classifying the galaxies according to different asymmetry types (see Paper I), with the difference that, since the NIR images are not sensible to dust extinction, no galaxies are classified as type 2.

In type 1, we have put all the “symmetric” galaxies or galaxies with “intrinsic” asymmetries related to star formation clumps and/or spiral arms. Examples of galaxies with a type 1 asymmetry are shown in Figure 12. In type 3 we see the most obvious evidence of galaxy interactions, under the form of tidal tails, plumes, connecting bridges, or a common envelop between galaxies. Examples of galaxies with a type 3 asymmetry are presented in Figure 13. Galaxies in type 4 are those which are highly asymmetric, but without an obvious cause. In type 5, we have regrouped the cases where the asymmetry may be due to a smaller mass satellite galaxy. Finally, in type 6 we have regrouped the cases where the asymmetry is accompanied by a possible double nucleus. Galaxies with type 4 can be found in Figure 14(a), those with type 5 can be found in Figure 14(b), and those with type 6 can be found in Figure 14(c).
The distribution of asymmetry types in the different samples, as found in the NIR, is presented in Figure 15. In the KIG sample, 88% of the galaxies are of type 1, the rest (12%) are classified as type 4 and type 5. Consequently, the fraction of symmetric galaxies in the NIR is higher than what is found in the optical.

As in the optical, the KPGs present a higher fraction (66%) of asymmetries related to interactions: 54% are of type 3 and 6% each are of types 4 and 5. The rest, 34% of the KPGs, are symmetric. For the HCGs, the number of asymmetric galaxies is also quite high, reaching 67% of the galaxies in our sample: 44% are type 3, 15% are type 4, 5% are type 5, and 3% are type 6.

In Table 12, we compare the fraction of galaxies belonging to each asymmetry type in the optical and NIR. We distinguish the same trends. Comparing the classification galaxy by galaxy, in general the asymmetry type is the same in both bands. The most notable difference is related to dust that does not affect the NIR images. Tidal tails and bridges seem as frequent in the

The NIR as in the optical. However, we do observe a higher fraction of asymmetric galaxies in the NIR than in the optical for the HCGs. Since we are not seeing this effect in the KPGs, this clearly states that something is different in the HCGs. Possibly, the interactions in the HCGs are at a more advanced stage and are affecting the oldest stellar population. Or possibly, interactions are now occurring in the absence of the usual evidence of star formation or nuclear activity. This last possibility is consistent with the dry merger hypothesis.

4.3. Color Gradients and Blue Cores

In normal early-type galaxies, color gradients make a galaxy core redder than the periphery (i.e., the gradient is negative; Peletier et al. 1990). These color gradients can be explained, in part, by the concentration of the older stellar population toward the center of the galaxies, and also, by an increase in stellar metallicity (Hinkley & Im 2001). Galaxy formation models suggest that such features in color gradients will form and stay unchanged for most of its lifetime. However, some elliptical galaxies are known to present color gradients that are flat or positive, i.e., bluer to the inner part (Michard 1999; Im et al. 2001; Yang et al. 2006). For these galaxies, models suggest that such features in color gradients can be the result of mergers or past interactions with gas-rich galaxies.

As in Coziol & Plauchu-Frayn (2007), we have searched for NIR blue cores in the early-type galaxies of our sample. The \( J - K' \) color gradient is defined as \( \Delta(J - K')/\log(r) \).
According to this definition, galaxies with blue cores have $\Delta (J - K')/\log(r) < 0$. For 29 early-type galaxies in the three samples, we were able to estimate this gradient. In these galaxies, we found colors consistent with blue cores or flat gradients in 10 out of 22 (45%) HCGs and 4 out of 6 (67%) KPGs. The only early-type galaxy in the KIG sample where we were able to estimate this gradient has $\Delta (J - K')/\log(r) > 0$. In Figure 16, we plot the $\Delta (J - K')/\log(r)$ gradients for early-type galaxies in our sample. Evidence for blue cores in early-type galaxies seems slightly higher in the KPGs than in the HCGs. This suggests slightly older ages for the interaction events in the CGs.

5. EVIDENCE OF STAR FORMATION PRODUCED BY INTERACTIONS

In the HCGs, we have found more evidence of asymmetries in the NIR than in the optical. This last phenomenon is not
observed in the KPGs. One possible interpretation is that in the KPGs the interactions involve a lot of gas, while in the HCGs these are occurring under dry conditions. To verify this assumption, we have searched for evidence of star formation induced by interaction in the different samples. In CGs, the star formation activity was already found to be low (Coziol et al. 1998, 2000, 2004; Martínez et al. 2010).

Using SDSS spectra together with the STARLIGHT\(^7\) spectral synthesis code (Cid Fernandes et al. 2005), we have classified the nuclear activity type for 241 (26%) galaxies in the KPG catalog with available spectra. In Table 13, we compare the activity type in the KPGs with those found by Martínez et al. (2010) for the HCG sample. We clearly distinguish a larger number of emission line galaxies in the KPGs than in the HCGs. Also, the dominant type of activity in the KPG galaxies is different, the majority of them being star-forming galaxies (SFGs), while those in the HCGs are low-luminosity AGNs. This comparison confirms that in the KPGs, interactions occur while galaxies are still rich in gas. This result also supports our interpretation that the color difference in terms of younger stellar populations in the KPGs is related to recent star formation events or AGN activity. For the 19 intermediate-type galaxies in our observed

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\(^7\) http://www.starlight.ufsc.br/
Figure 14. Examples of galaxies with (a) type 4 asymmetry—cause is not obvious; (b) type 5—companion appearing near center; (c) type 6—possible double nucleus. The $J$-band images are displayed on logarithmic scales together with their residual images.

Figure 15. Distribution of asymmetry types in different environments.

Table 13
Distribution of the Nuclear Activity Type in the HCG and KPG

| Sample | Number | No Emission | Emission | SFG | TO | AGN |
|--------|--------|-------------|----------|-----|----|-----|
| HCG    | 270    | 100 (37%)   | 170 (63%)| 54  (32%) | 39  (23%) | 77 (45%) |
| KPG    | 241    | 43 (18%)    | 198 (82%)| 111 (56%) | 35  (18%) | 52 (26%) |

Notes. Columns: (1) sample identification, (2) number of galaxies with available spectra, (3) fraction of galaxies with no emission lines, (4) fraction of galaxies showing emission lines, (5) fraction of star-forming galaxies, (6) fraction of transition objects, and (7) fraction of AGNs (Sy2, LINER, and Sy1). Data for the HCG galaxies have been obtained from Martínez et al. (2010).

Comparing the optical (Paper I) and NIR analyses, we saw that the properties of galaxies with different morphological types are much more similar in the NIR than in the optical and this is independent of the environment of the galaxies. This is consistent with older populations lying at lower energy levels in the gravitational potential well of their galaxies. Consequently,

6. DISCUSSION
the asymmetry level induced by interactions is expected to be higher in the optical than in the NIR. This is because it requires much more energy to disrupt these stars.

On the other hand, asymmetric structures related to interactions seem as frequent in the NIR as in the optical. Moreover, there seems to be almost a one-to-one relation in the case of tidal tails and bridges. This confirms our interpretation that asymmetries are related to interactions: these correspond to real mass redistributions.

The fact that we find the HCGs to be less compact than in other environments is, consequently, quite revealing. This observation suggests that the orbits of the stars in the HCGs are more energetic. Such an effect would be achieved by increasing the number of interactions: the larger the number of interactions and the higher the energy of the stars, the more energetic, or less compact, their orbits are in equilibrium. A galaxy in isolation, on the other hand, would be expected to be much more compact, which seems consistent with our observations for the KIGs. For the CGs, the hypothesis of multiple interactions is also consistent with the numerous early-type galaxies found in this sample (Hickson et al. 1988). Our results agree with previous works in the sense that a considerable fraction of galaxies in CGs show perturbations related to interactions and/or mergers (Rubin et al. 1991; Mendes de Oliveira & Hickson 1994; Verdes-Montenegro et al. 2001).

The question that remains for the CGs is: what is the timescale of the interaction process? Is the evolution of galaxies accelerated by numerous interactions or are the galaxies in CGs more morphologically evolved because they began to interact at an earlier time? The multiple evidence of interactions in the CGs, both in the optical and NIR, suggest these galaxies are clearly not in equilibrium. Therefore, CGs could not have formed that long ago in the past.

For the pairs of galaxies, we may easily assume that the interactions are relatively recent. These galaxies are formed in low-density environments and it took a Hubble time for two of them to meet and interact. This interpretation is consistent with our observations. In the KPGs, the stellar populations in the central region of the galaxies with different morphologies seem younger, in general, than in the HCGs. This is consistent with the spectroscopic evidence, which shows a higher level of star formation in the KPGs compared to the HCGs.

One key difference between the HCGs and the KPGs seems to be that in the CGs, interactions are happening under dry conditions, confirming what we observed in Coziol & Plauchu-Frayn (2007). The fact that we do not see such a phenomenon in the KPGs could be due to very recent interactions in these systems (this is supported by spectroscopy). In the CGs, a first round of interactions would have produced the numerous early-type galaxies we now observe. Possibly when they formed, the CGs would have experienced a more active phase of star (and AGN) formation. But now that the gas is exhausted, the galaxies in CGs, assuming merging orbits, can only interact under dry conditions. For the KPGs, we do not know what their future will be. Possibly those are systems with high energy orbits that will interact again only after an extremely long time has passed. In the case of the CGs, evidence of dry interaction conditions would thus be evidence that galaxies in these systems are now in merging orbits. Consequently, their formation cannot be that far in the past.

7. CONCLUSION

Our analysis suggests that pairs of galaxies are young structures: the galaxies in pairs formed in and spent most of their life in relative isolation and are just beginning to interact. This behavior would be typical of low-density environments, or what is found at the periphery of large-scale structures.

On the other hand, galaxies in CGs are obviously more morphologically evolved and have suffered more interactions. However, based on the abundant evidence of interactions in both the NIR and the optical, these systems cannot be in equilibrium. In particular, evidence for dry interactions in CGs is consistent with the hypothesis that galaxies are in merging orbits. Consequently, CGs cannot be extremely old.

Cosmologically speaking, the difference in formation time between pairs and CGs may be relatively small. That is, the two phenomena are probably typical of the formation of structures in low-density environments and consequently their respective formation represents relatively recent events compared to the formation of larger and more massive structures.

According to this interpretation, one would not expect systems like local CGs to exist at high redshifts. CGs may have formed in the past, but these would have been much more massive than what we find today and such systems would have been expected to merge with others to form cluster of galaxies (Coziol et al. 2009).

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