

## INTERNAL KINEMATICS OF SPIRAL GALAXIES IN DISTANT CLUSTERS<sup>1</sup>

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Received 2003 July 11; accepted 2003 September 8; published 2003 November 13

### ABSTRACT

We introduce our project on galaxy evolution in the environment of rich clusters, aiming at disentangling the importance of specific interaction and galaxy transformation processes from the hierarchical evolution of galaxies in the field. Emphasis is laid on the examination of the internal kinematics of disk galaxies through spatially resolved multiobject spectroscopy with FORS at the Very Large Telescope. First results are presented for the clusters MS 1008.1–1224 ( $z = 0.30$ ), CI 0303+1706 ( $z = 0.42$ ), and CI 0413–6559 (F1557.19TC;  $z = 0.51$ ). Out of 30 cluster members with emission lines, 13 galaxies exhibit a rotation curve of the universal form rising in the inner region and passing over into a flat part. The other members have either intrinsically peculiar kinematics (4), too strong geometric distortions (9), or a too low signal-to-noise ratio (4) for a reliable classification of their velocity profiles. The 13 cluster galaxies for which a maximum rotation velocity could be derived are distributed in the Tully-Fisher diagram very similar to field galaxies from the FORS Deep Field that have corresponding redshifts and do not show any significant luminosity evolution with respect to local samples. The same is true for the seven galaxies observed in the cluster fields that turned out not to be members. The mass-to-light ratios of the 13 Tully-Fisher cluster spiral galaxies cover the same range as the distant field population, indicating that their stellar populations were not dramatically changed by possible cluster-specific interaction phenomena. The cluster members with distorted kinematics may be subject to interaction processes, but it is impossible to determine whether or not these processes also lead to changes in the overall luminosity of their stellar populations.

*Subject headings:* galaxies: clusters: individual (CI 0303+1706, CI 0413–6559, MS 1008–1224) — galaxies: evolution — galaxies: kinematics and dynamics — galaxies: spiral

### 1. INTRODUCTION

Galaxy clusters provide a special environment for their members. In contrast to the field, the number volume density of galaxies is high, and the relative velocities are large. The gravitational potential of a cluster is filled by the intracluster medium (ICM), a hot X-ray-emitting gas, and the overall mass-to-light ratio is much larger than for the individual galaxies, indicating the presence of vast amounts of dark matter. This environment exerts a strong influence on the evolution of the cluster galaxies superposed on the (field) evolution that arises from the hierarchical growth of objects and the declining star formation rates over cosmic epochs. Besides tidal interactions between galaxies, including merging, as can also be observed in the field, cluster members are affected by cluster-specific phenomena related to the ICM (like ram pressure stripping) or the structure of the cluster (like harassment). For a recent overview, see the third volume of the Carnegie Observatories Astrophysics Series.<sup>2</sup> Imprints of these interactions can be seen not only in present-day clusters, but they also manifest themselves in a strong evolution of the population of cluster galaxies. One example is the photometric Butcher-Oemler effect of an increasing fraction of blue galaxies with redshift (e.g., Butcher & Oemler 1978) implying a rising percentage of star-forming galaxies. Another example is the rapid decline of the abundance of lenticular galaxies (S0) from the dominant population in

local clusters to a few percent at a look-back time of  $\sim 5$  Gyr (e.g., Dressler et al. 1997). These observations have led to the question whether field spiral galaxies falling into a cluster can be subject to such morphological transformations that they appear as S0 galaxies today.

Independent of whether this overall scenario is true or not, the observed tidal interactions (either between galaxies or with the cluster potential) may cause substantial distortions on both the structure and the kinematics of the galaxies involved. Indeed, Rubin, Waterman, & Kenney (1999), for example, found that half of their sample of 89 disk galaxies in the Virgo Cluster exhibit kinematic disturbances ranging from modest (e.g., asymmetric) to severe (e.g., truncated curves) peculiarities. On the other hand, many local cluster galaxies, for which only H I velocity widths (in contrast to spatially resolved velocity profiles) were measured, follow a tight Tully-Fisher (TF) relation similar to field spiral galaxies (e.g., Giovanelli et al. 1997). This TF relation connects the luminosity of the stellar population of a galaxy to its internal kinematics, which are dominated by the presence of a dark matter halo (Tully & Fisher 1977).

On the other hand, it is not yet clear whether the halo of dark matter and, therefore, the total mass of a galaxy can also be affected by certain interaction phenomena. In numerical simulations of the evolution of substructure in clusters by Springel et al. (2001), the dark matter halo of a galaxy that falls into the cluster is truncated via tidal interactions so that the mass-to-light ratio of a galaxy gets reduced during its passage to the cluster core. Gnedin (2003) simulates the tidal field along galactic orbits in hierarchically growing clusters and finds that

<sup>1</sup> Based on observations collected at the European Southern Observatory, Cerro Paranal, Chile (ESO proposals 64.O-0158, 64.O-0152, and 66.A-0547).

<sup>2</sup> See <http://www.ociw.edu/ociw/symposia/series/symposium3/proceedings.html>.

about 40% of the dark halo of a massive galaxy ( $V_{\max} = 250 \text{ km s}^{-1}$ ) is lost between  $z = 5$  and  $z = 0$ . But the rotational velocity at  $\sim 5$  disk scale lengths is predicted to hardly change (decrease by  $\sim 2\%$ ).

## 2. OUR PROJECT

Since, in models of hierarchically growing structure, clusters are still in the process of forming at  $z \lesssim 1$  in the concordance cosmology, a higher infall rate and more interactions are expected at redshifts  $0.3 \lesssim z \lesssim 1$  (e.g., Kodama & Bower 2001). With the availability of large telescopes, it is now feasible to conduct spatially resolved spectroscopy of the faint galaxies at these redshifts in order to observationally test these predictions. Therefore, we have performed a large campaign at the Very Large Telescope (VLT) targeting seven distant rich clusters with  $0.3 \lesssim z \lesssim 0.6$ . The clusters were chosen from a very limited list with existing *Hubble Space Telescope* (HST)/WFPC2 imaging (mainly the core regions) at the time the project started (1999) and that are accessible with the VLT. MS 1008–12 has no HST imaging but was included since it was imaged extensively during the FORS science verification time. The main goal is to derive the two-dimensional internal kinematics of disk galaxies from emission lines. In combination with measurements of star formation rates, luminosities, and structural parameters, we aim to disentangle the effects of different interaction processes and to find out about their respective actual effectiveness and importance for galaxy evolution.

In this Letter, we present the results for the first three clusters of our survey: MS 1008–12 ( $z = 0.30$ ), Cl 0303+17 ( $z = 0.42$ ), and Cl 0413–65 ( $z = 0.51$ ). They were observed with FORS1 in multiobject spectroscopy (MOS) mode, while the other four clusters (Cl 0016+1609, MS 0451.6–0305, ZwCl 1447.2+2619, and MS 2137.3–2353) had Mask Exchange Unit (MXU) multiobject spectroscopic observations with FORS2 requiring different reduction techniques that will be presented in future papers. While in Jäger et al. (2003, hereafter Paper II) we give all the data that can be deduced from each single spectrum, in this Letter we analyze only the late-type galaxies that exhibit spatially resolved emission. One setup in the MOS mode of FORS1 provides 19 individual slitlets. For each cluster, two setups have been designed with different rotation angles for the instrument. Using grism 600R and slit widths of  $1''$ , the spectra have a dispersion of  $\sim 1.08 \text{ \AA pixel}^{-1}$ , a spectral resolution of  $R \approx 1200$ , and typical wavelengths of  $\lambda \approx 5200\text{--}7400 \text{ \AA}$ . In standard configuration, FORS has a field of view of  $6.8 \times 6.8$  with a spatial scale of  $0.2 \text{ pixel}^{-1}$ . To achieve our signal-to-noise ratio requirements of  $S/N \gtrsim 5$  in the emission lines of an  $R \lesssim 23$  galaxy, the total integration time was set to  $\sim 2$  hr. Seeing conditions ranged between  $0.7$  and  $1.3$  FWHM.

Spatially resolved velocity profiles  $V_{\text{rot}}(r)$  were determined from either the [O II]  $\lambda 3727$ , H $\beta$ , or [O III]  $\lambda 5007$  emission line. In eight cases, two lines with sufficient S/N were visible, and these were then treated separately, yielding consistent results. The spectral profile of an emission line was fitted by a Gaussian (in the case of [O II]), the spectral profile was fitted by a double Gaussian after applying a median filter window of typically  $0.6$  to enhance the S/N stepping along the spatial axis. Since the apparent disk sizes of spiral galaxies at intermediate redshifts are only slightly larger than the slit width ( $1''$ ), the slit covers a substantial fraction of the two-dimensional velocity field. Therefore, the spectroscopy is an integration perpendicular to the slit's spatial axis. Because of this effect, the maximum rotation velocity  $V_{\max}$  cannot be determined

“straightforwardly” from the observed rotation. As described in Ziegler et al. (2002) and Böhm et al. (2003), we overcome this problem by simulating the long-slit spectroscopy of each galaxy individually. In short, a two-dimensional velocity field is created by assuming a specific rotation law that is weighted by the galaxy's luminosity profile and convolved to match the seeing at the time of our observations. Taking into account the galaxy's inclination, position angle, and disk scale length, a synthetic rotation curve is generated with  $V_{\max}$  as the only remaining free parameter.  $V_{\max}$  is then determined by matching the synthetic to the observed velocity profile. For the galaxies analyzed here, we used for the model rotation curve a simple parameterization with a linearly rising inner part that turns over into a flat outer part. But as is demonstrated by Böhm et al. (2003),  $V_{\max}$  is hardly changed when the universal rotation curve by Persic, Salucci, & Stel (1996) is used instead. The inclinations, position angles, and scale lengths were derived via two-dimensional  $\chi^2$  fits of exponential disks to the galaxies' profiles in FORS images. The FWHMs were  $0.59$  (MS 1008–12),  $0.77$  (Cl 0413–65), and  $1.0$  (Cl 0303+17), respectively. The fits accounted for the point-spread function. Spiral galaxies with too low an inclination ( $i \lesssim 20^\circ$ ) have not been used for the  $V_{\max}$  derivation.

Galaxy luminosities were derived from total magnitudes of FORS images in the  $V$  band (MS 1008–12) or the  $I$  band (Cl 0413–65 and Cl 0303+17) as measured with SExtractor (Bertin & Arnouts 1996). Observed magnitudes were corrected for Galactic (from Schlegel, Finkbeiner, & Davis 1998) and intrinsic extinction (following Tully & Fouque 1985), transformed to rest-frame Johnson  $B$  magnitudes according to their spectrophotometric type using model spectral energy distributions corresponding to Sa, Sb, Sc, and Sdm, and calculated for a flat  $\Omega_\Lambda = 0.7$  cosmology ( $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). The average overall error in the photometry is estimated to be  $\leq 0.2$  mag.

## 3. KINEMATICS OF CLUSTER SPIRAL GALAXIES

The MOS mode of FORS1, which was the only multiplex technique available for the first observations of our campaign, has some disadvantages for the spectroscopy of spiral galaxies in clusters. These are removed when using the MXU mode of FORS2, which we used for the other four clusters of our survey. First, the 19 slitlets of fixed length ( $\sim 22''$ ) have only 1 degree of freedom for placing a slitlet onto an object. This leads to somewhat inefficient coverage of cluster member candidates, and many slitlets must be filled by strongly relaxing the ideal selection criteria. Second, once a certain rotation of the field is chosen, all 19 slitlets have the same orientation on the sky. Ideally, the slit should be placed along the major axis of a galaxy to probe its rotation around the center. Although we have targeted each cluster with two different setups, the deviation  $\delta$  between slit angle and position angle was rather large in some cases, leading to geometric distortions of the observed velocity profile that could not be corrected for. These galaxies are not used in the further analysis of the internal kinematics here but are valuable ingredients for future studies of, e.g., star formation rates or structural properties of cluster members.

As is specified in more detail in Paper II, our method of selecting cluster spiral candidates was different for each cluster because of the limited information of published studies. The most comprehensive source available was for MS 1008–12, for which we exploited a catalog of  $\sim 80$  cluster members with published spectral types (Yee et al. 1998). A list of candidates in Cl 0413–65 was prepared by comparing optical–near-in-

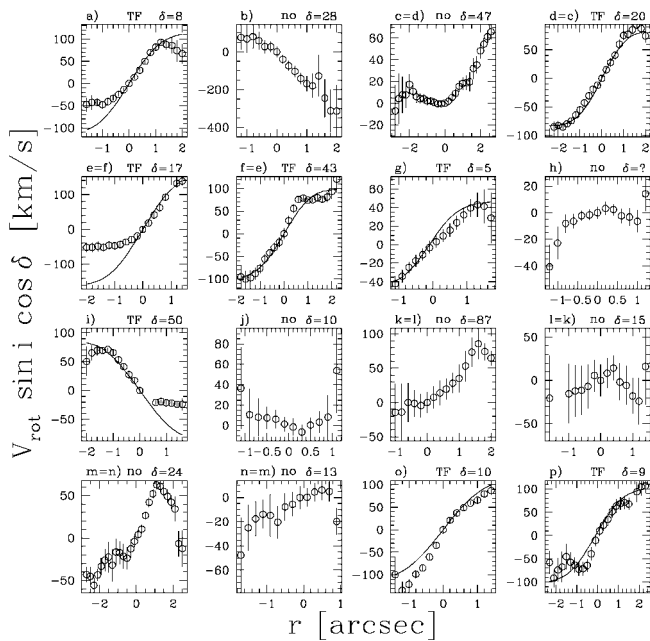


FIG. 1.—Spatially resolved velocity profiles for 12 disk galaxies in the cluster MS 1008–12 at  $z = 0.30$ . Note that panels c=d, e=f, k=l, and m=n represent the same galaxy, but observed with different slit positions (the rotation angles of the two MOS masks differed by  $67^\circ$ ). Panels a–p are ordered according to the distance of the galaxies from the cluster center. Values of the maximum rotation velocity could be determined for cases a, d, e, f, g, i, o, and p indicated by the label “TF.” These galaxies enter the TF relation shown in Fig. 2. In all other cases, the kinematics are too disturbed (for panels c and k, this may be due to a large mismatch angle  $\delta$ ). For the TF cases, the solid lines denote the *projected* model curves that were produced from the best-fitting two-dimensional velocity fields simulating the observational circumstances. Note that the maximum values of these fits are not the intrinsic  $V_{\max}$  values needed for Fig. 2.

frared colors by Stanford et al. (2002)<sup>3</sup> with evolutionary stellar population models of an updated version of Bruzual & Charlot (1993). For CI 0303+17, we mainly utilized the spectroscopic catalog of Dressler & Gunn (1992). MOS slitlets that could not be filled by galaxies from our input lists were placed on objects selected according to their structural appearance and magnitudes as measured on our FORS images. If no suitable candidate for a late-type galaxy was available, the slitlet was placed on an elliptical candidate since understanding the phenomenon of galaxy transformation requires the analysis of the whole galaxy population of a cluster.

Redshifts and spectral types could be determined for 12/13 spiral/elliptical members of MS 1008–12 (plus 4/2 spiral/elliptical field galaxies), 8/1 spiral/elliptical members of CI 0413–65 (plus 11/6 spiral/elliptical field galaxies), and 10/7 spiral/elliptical members of CI 0303+17 (plus 15/0 spiral/elliptical field galaxies). While the early-type galaxies will be discussed in a future paper, we here concentrate on the emission-line galaxies. As was pointed out by Verheijen (2001), only galaxies with a rotation curve that rises in the inner region and then clearly turns into a flat part should be used for a TF diagram. In such a case, the measured  $V_{\max}$  is representative of the influence of the dark matter halo on the galaxy’s kinematics and is indicative of the total dynamical mass of the galaxy. For our three clusters, we were able to determine  $V_{\max}$  for 7/5/1 different member galaxies, respectively (and 1/5/1 field spiral galaxies). The remaining cluster

<sup>3</sup> Kindly provided to us by A. Stanford well in advance of their actual publication.

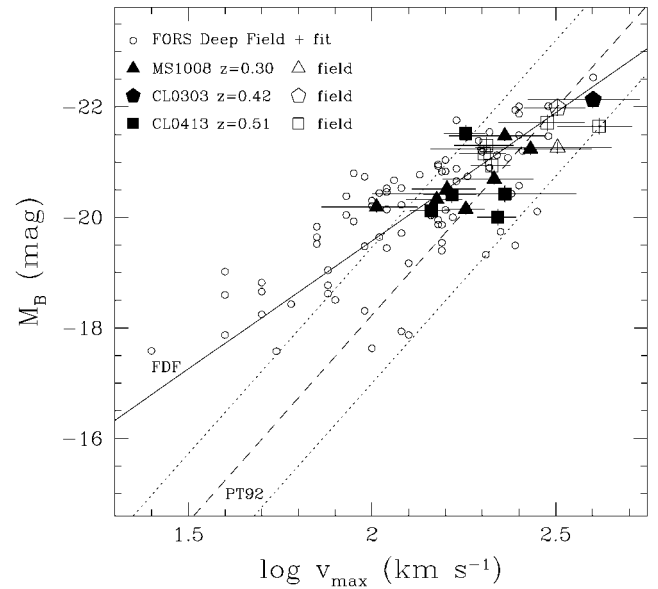


FIG. 2.—TF diagram of cluster spiral galaxies in MS 1008–12 (filled triangles), CI 0413–65 (filled squares), and CI 0303+17 (filled pentagon). Also shown are seven field objects (open symbols) that were serendipitously observed. In comparison with the FORS Deep Field sample of 77 field galaxies (Ziegler et al. 2002; Böhm et al. 2003) with  $0.1 < z < 1$  (open circles), the cluster galaxies are similarly distributed and do not deviate significantly from the linear fit to the FORS Deep Field sample (solid line). The cluster members follow the same trend with respect to the local TF relation (the fit  $\pm 3\sigma$  to the PT92 field sample is given) as the distant field galaxies with the brightest galaxies exhibiting the smallest luminosity evolution.

spiral galaxies either have too low an S/N for their emission lines to spatially analyze the internal kinematics (in 0/0/4 cases), have too low an inclination  $i$  or too large a mismatch angle  $\delta$  (in 1/3/5 cases), or exhibit intrinsic distortions (in 4/0/0 cases).

In Figure 1, we show as an example position-velocity diagrams for all member galaxies in MS 1008–12 that have sufficient S/N. Of the 12 members, of which four were observed twice with different slit angles with respect to their major axis, seven exhibit the “classical” rotation-curve shape rising in the inner part and turning over to a flat regime (labeled “TF”). Four members clearly show disturbed kinematics (panels b, j, l, and m). The distortion seen in panel m (=n) most probably arises from a bar that is readily visible in the direct image. Two “double hits” were observed with very big mismatch angles (panels c and k) so that their velocity profiles look peculiar. In one case (panel h), the object fell onto the slitlet by chance and is too weak (small) to derive its structural parameters. In the figure, the galaxies are ordered according to their projected distance to the cluster center (ranging from 285 to 1230 kpc). There is no trend visible for the rotation-curve form as a function of clustercentric distance; i.e., distorted velocities are not uniquely tied to the central region. But since our observations cover only the region within the virial radius of the cluster ( $\sim 1880$  kpc), this is in accordance with dynamical models in which the galaxy population of a cluster is well mixed within that region (Balogh, Navarro, & Morris 2000). In particular, we most probably do not have any new arrivals from the field in our sample.

#### 4. THE TULLY-FISHER RELATION

In Figure 2, we present the TF diagram for the distant cluster galaxies. Only those galaxies for which  $V_{\max}$  could be deter-

mined enter the plot. The ordinate gives the rest-frame absolute Johnson  $B$ -band magnitudes. We also show the position of those field galaxies that were serendipitously observed in the cluster fields and that have  $0.4 < z < 0.6$  (three spiral galaxies at  $z = 0.61$  may be members of a background cluster behind Cl 0413–65). For comparison, we include the distant field galaxies from the FORS Deep Field (Heidt et al. 2003) that were observed with exactly the same instrumental setup (Ziegler et al. 2002; Böhm et al. 2003). The linear bisector fit to this sample is flatter than the slope fitted to the local sample of Pierce & Tully (1992, hereafter PT92), which is given with its  $\pm 3 \sigma$  deviations.

The distant cluster spiral galaxies are distributed very much like the field population that covers similar cosmic epochs ( $0.1 < z < 1$ , with the bulk of galaxies at  $z \approx 0.3$  and  $\approx 0.6$ ). No significant deviation from the distant field TF relation is visible, and the cluster sample has no increased scatter, but the low number of cluster members prohibits any quantitative statistical analysis. Nevertheless, we conclude that the mass-to-light ratios of the observed distant cluster spiral galaxies cover the same range as the distant field population, indicating that their stellar populations were not dramatically changed by possible cluster-specific interaction phenomena. In particular, we do not detect any significant overluminosities, as would be expected in the  $B$  band if strong starbursts had occurred in the recent past in the examined cluster galaxies. With respect to the TF relation followed by local galaxies (e.g., PT92), our cluster sample follows the same trend as the FORS Deep Field galaxies. Since mostly only the bright galaxies made it into the TF diagram, the cluster members occupy a region where no significant luminosity evolution is visible.

However, we emphasize that this conclusion is true only for those objects that enter the TF diagram. Since a significant fraction of our cluster galaxies cannot be used for a TF analysis because of their distorted kinematics, the above conclusions are not generally valid for the whole cluster sample. The objects with intrinsically peculiar velocity curves may actually be subject to ongoing interactions, or they may have experienced recent interactions. Such processes most probably also influence the stellar populations of a galaxy changing its integrated luminosity as well. Tidal interactions, for example, could distort the spiral arms while at the same time inducing starbursts, leading to enhanced luminosities. Since we do not know where the galaxies with peculiar kinematics lie in the TF plane, it is not possible to decide whether a particular galaxy has an increased or a decreased luminosity. Overall, these galaxies span

a very similar range in apparent magnitudes to the TF cluster members.

Exploring the spatially resolved kinematics of disk galaxies in distant clusters has only recently become feasible. Milvang-Jensen et al. (2003) studied a sample of seven spiral galaxies in the cluster MS 1054.4–0321 at  $z = 0.83$  with FORS at the VLT in a similar configuration as our own spectroscopy. Compared with a number of field spiral galaxies at corresponding redshifts, which were observed at the same time, they find that the cluster members have brighter  $B$  luminosities by  $\sim 0.5$ – $1$  mag ( $\sim 1.5 \sigma$ – $2 \sigma$  significance) for their rotational velocities. The difference in the average brightening of our cluster members is hardly significant and may be due to a combination of low-number statistics and systematic deviations. But we also cannot rule out the possibility that the differences are real and that they may be connected to the higher redshift of MS 1054.4–0321 or to other characteristics of that cluster.

Metevier (2003) examined galaxies in the cluster Cl 0024+1654 ( $z = 0.40$ ) with the Keck 10 m telescope. The 10 galaxies that appear in their TF diagram have a larger scatter than the local PT92 sample, but they show no evidence of an evolution of the zero point. The authors argue that processes acting on the cluster galaxies some time before the look-back time of the observations involving either starbursts or a truncation of star formation may have caused a decreased or an increased mass-to-light ratio, respectively, which is manifested in the increased scatter.

In a future paper, we will present our analysis for the other four clusters of our campaign. With more cluster member galaxies both in the TF diagram and with peculiar kinematics, we hope to be able to quantitatively investigate the galaxy evolution in rich clusters and to give statistical tests as well.

We acknowledge the thorough comments by the referee. We are very grateful to S. Wagner (Heidelberg), U. Hopp (München), and R. H. Mendez (Hawaii) for performing parts of the observations, and we thank the ESO and the Paranal staff for their efficient support. We also thank the PI of the FORS project, Professor I. Appenzeller (Heidelberg), and Professor K. J. Fricke (Göttingen) for providing guaranteed time for our project. We also acknowledge fruitful discussions with B. Milvang-Jensen (MPE Garching) and M. Verheijen (Potsdam). This work has been supported by the Volkswagen Foundation (I/76 520) and the Deutsche Forschungsgemeinschaft (Fr 325/46-1 and SFB 439).

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