THE UNIVERSALITY(?) OF DISTANCE-INDICATOR RELATIONS

S. DJORGOVSKI, R. DE CARVALHO, and M.-S. HAN
California Institute of Technology
Pasadena, CA 91125, USA.

ABSTRACT. We examine the origin of distance-indicator relations for galaxies, and the possibility that they may vary with the large-scale environment. The relations reflect formative and evolutionary processes of galaxies, and contain some information about them. They are expected to depend on the environment in a complex manner. There are hints that both the Tully-Fisher relation for the spirals, and the $D_n - \sigma$ relation for the ellipticals may depend on the parent cluster properties such as richness, velocity dispersion, or galaxy number density, but these tentative dependences are hard to separate from the selection effects. If the distance-indicators vary from one cluster to another, some of the large peculiar motions claimed in the literature are partly spurious. Until the environmental effects on distance-indicator relations are better understood, their use for the mapping of large-scale velocity fields and measurements of the far-field Hubble constant may be premature.

The distance-indicator relations, e.g, Tully-Fisher (TF), Faber-Jackson (FJ), the "fundamental plane" of elliptical galaxies and bulges (FP), etc., play a crucial role in detremining the H_0, and are essential for the measurements of large-scale velocity fields. In order for the relations to be usable for these purposes, they have to be universal, that is, same in all large-scale structure (LSS) environments, at a high level of repeatibility. (Recall that at the redshift of 5000 km s^{-1}, a 10% distance error translates into a false peculiar velocity of 500 km s^{-1}.) The distance-indicator relations are tools in exploring the LSS and the associated Hubble flow and deviations from it, and like all tools, they must have their limits of accuracy. Our purpose here is to explore such limits, by looking at the origin of distance-indicator relations, their sensitivity to the formative and evolutionary processes for galaxies in different environments, and to compare the relations derived for individual clusters using the available large and homogeneous data bases. Whether the distance-indicator relations are universal or not, they contain valuable information about the galaxy formation.

The physics underlying the distance-indicator relations is actually very simple, the same for all of them, and clearly universal. The astrophysics implied by their existence is complex, and highly nontrivial; it contains practically all the puzzles of galaxy formation and evolution.

For any galaxy bound by the newtonian gravity the following energy equation must hold:

$$\frac{GM}{\langle R \rangle} = k_E \frac{\langle V^2 \rangle}{2} \tag{1}$$

where G is the gravitational constant, M is the galaxy mass, $\langle R \rangle$ a suitable mean radius defined so that the left side of the Eq.(1) is the potential energy, $\langle V^2 \rangle/2$ a mean kinetic energy per unit mass, and k_E the virialization constant: $k_E > 1$ for a bound system, and $k_E = 2$ for a virialized one. Clearly, the k_E is determined by the overal energy dissipation during the formation of a galaxy, or at least its visible components.

Let an operationally defined, observed radius of a galaxy derived in a non-isophotal way (e.g., the core radius in a Hubble or King model fit, the de Vaucouleurs' r_e, or the e-folding radius of an exponential disk) be:

$$R = k_R \langle R \rangle \tag{2}$$

The parameter k_R thus reflects the density structure of a galaxy. Similarly, let an operationally defined, observed velocity scale of some sort (e.g., the maximum rotational velocity of a spiral, or the central velocity dispersion of an elliptical) be defined as:

$$V^2 = k_V \langle V^2 \rangle \tag{3}$$

The parameter k_V reflects the kinematical structure of a galaxy, e.g., the velocity dispersion tensor with all of its anisotropies in elliptical, the breakdown of the kinetic energy between the circular and random motions, etc. Finally, let the I be an operationally defined mean surface brightness of a galaxy, and the relation between the luminosity L, I, and R:

$$L = k_L I R^2 \tag{4}$$

The parameter k_L thus reflects the luminosity structure of a galaxy in the given bandpass, which in general is not the same as its density structure. Obviously, the parameters k_R, k_V, and k_L depend on the operational definitions of observables, whereas k_E does not, and it represents an intrinsic quality of a galaxy.

With these definitions, it is easy to derive from Eq.(1):

$$R = K_{SR} V^2 I^{-1} (M/L)^{-1} \tag{5}$$

and

$$L = K_{SL} V^4 I^{-1} (M/L)^{-2} \tag{6}$$

where (M/L) is the global mass-to-light ratio of a galaxy, and the combined structural parameters K_{Sx} are:

$$K_{SR} = \frac{k_E}{2G k_R k_L k_V} \tag{7}$$

and

$$K_{SL} = \frac{k_E^2}{4G^2 k_R^2 k_L k_V^2} \tag{8}$$

Let us call the Eqs.(5) and (6) *the generalized distance indicator relations*, combining the distance-dependent quantities R and L with the distance-independent expressions on the right-hand sides. In practice, the Eq.(5) comes in the form of the FP relation,

$$R \sim V^A I^B \tag{9}$$

where the observed values of coefficients A and B are about 1.4 and −0.9 (Djorgovski & Davis 1987). The FP relation also comes in the guise of the $D_n - \sigma$ relation proposed by Dressler *et al.* (1987). As shown by these authors, the two forms are equivalent, providing that all galaxies considered have the same integrated light profiles (which may, but do not have to correspond to the de Vaucouleurs' profile), or in our terminology, that k_R and k_L are the same for all galaxies (see also Phillipps 1988b). The Eq.(6) appears in the guises of TF and FJ relations,

$$L \sim V^C \tag{10}$$

where the observed values of coefficient C are generally close to 4. Some other distance-indicator relations proposed in the literature can be traced to these forms, and the underlying physics is the same. [†]

If the isophotally defined radii or magnitudes are used instead, that effectively ammounts to absorbing the surface brightness term into the R or L. In fact, that is commonly done for the TF relation, and also with the FP in its $D_n - \sigma$ incarnation.

In order for the distance-indicator relations of these forms to work, the products $K_{SR}(M/L)^{-1}$ and $K_{SL}(M/L)^{-2}$ have to be *power-law functions of the explicite variables R, L, I, or V alone.* The deviations of the observed coefficients A, B and C from their "canonical" values of 2, −1, and 4, define these functions. If these functions are not pure power-laws, the distance-indicator relations become nonlinear. The cosmic scatter and possible variations in the intercepts of the relations may reflect the dependence on other, unaccounted for variables, e.g., the properties of the LSS environment. This defines the limits of applicability of distance-indicator relations.

All of the constituent parameters of K_{SR}, K_{SL}, and (M/L) can depend on the formative and evolutionary histories of galaxies. Our present understanding of galaxy formation is that it generally consists of a series of dissipative merging and infall processes, most of which can be conditioned by the large-scale environment (e.g., Silk & Norman 1981; Silk 1987; etc.). Some of the relevant processes may include: mergers and violent relaxation; gradual infall and formation of disks; tidal shocks, tidal torquing, and the origin of angular momenta; dark halo stripping, and gas sweeping; biasing of the star formation by the neighboring protogalaxies via their radiation fields and galactic winds; metallicity enrichment and gas retention in protocluster cores, and its effects on the stellar IMF; cooling flows and abnormal IMF's; etc. The environment thus affects not only the supply of the galaxy-building material, but also the dynamical structure of the final products (for example, the velocity anisotropies

[†] The derivation of the $L \sim V^4$ relation from the Gott-Rees (1975) hierarchy by Faber (1982), and the constraint on the initial density perturbation spectrum index from there may be incorrect, as it ignores some of the terms in a more complete Eq.(6). Inclusion of the missing terms leads to a virial theorem tautology. Unlike the dissipationless, mostly unrelaxed LSS, galaxies do not retain any memory of the initial density perturbation spectrum: their properties are dertermined by the dynamical relaxation and merging processes, and by dissipation (cooling), which takes them out of the clustering hierarchy, and defines them as units.

of ellipticals are dynamical fossiles of the past mergers), the primordial IMF and thus the stellar (M/L), the ratio of the dark and visible matterial, etc. Most of these phenomena are generic, i.e., independent of the exact scheme of the LSS formation (top-down vs. bottom-up, CDM, or other scenarios).

Galaxian properties are thus expected to depend on the LSS environment, and this is indeed observed. The most prominent effect is the morphology-density relation (Dressler 1980; Postman & Geller 1984), which is closely related to the morphology-clustering relation (Davis & Geller 1976) and morphology-LSS topology relation (Giovanelli *et al.* 1986). Related to that is the surface brightness-clustering relation (Davis & Djorgovski 1985; Djorgovski & Davis 1986; but see also Bothun *et al.* 1986). There are indications that the galaxy luminosity function varies with the environment (Binggeli 1987; Giovanelli & Haynes 1988). Finally, there are controversial, but intriguing alignment effects (Djorgovski 1987a, and references therein). The crucial question is, are there large-scale dependences of galaxian properties relevant for the distance-indicator relations within a given Hubble type, or in the case of the TF relation, within the whole sequence of spirals?

The (M/L) is one of the principal parameters of interest here, and perhaps the easiest one to track down and measure. Large-scale variations in the (M/L) are naturally expected in many, and perhaps all scenarios of LSS and galaxy formation (Hoffman *et al.* 1982; Silk 1988). Such variations are indeed one of the cornerstones of the whole idea of biased galaxy formation (see, e.g., Dekel & Rees 1987 for a review). The data on clusters are hard to come by, but there are some indications that the (M/L) ratios of galaxy clusters vary by a factor of $3-10$, and perhaps depend on the cluster mass (N. Bahcall 1981; Schectman & Dressler 1988). If there are such variations in (M/L), the essential question is, are they coupled to the individual galaxies? The (M/L) appears to vary along the Hubble sequence (Tinsley 1981; Rubin *et al.* 1982). That can translate into a type-dependence of the TF relation, and from there, via morphology-density relation, into a dependence on the cluster properties. If one assumes a constancy of the K_{SR} parameter for ellipticals, then from the observed equation of the FP, a dependence of (M/L) on mass follows, with a considerable residual scatter (Faber *et al.* 1987; Djorgovski 1987b); it is not yet clear if there is a dependence on the environment, but such test is in principle possible. Variations of (M/L) by a factor of 2 even within a single Hubble type are easily allowed by the present data.

The mean surface brightness I reflects the star formation history of a galaxy, and thus merger-caused starbursts or gas sweeping. There is some disagreement as whether the effects of sweeping are evident in the properties of cluster spirals (Bothun *et al.* 1984, 1985b; Giovanelli *et al.* 1986), but that is clearly a possibility. Phillipps (1988a) finds a systematic difference in surface brightness between the H I deficient and normal spirals in the Virgo cluster.

The parameter k_E is directly related to the degree of energy dissipation (cooling) during the formation of a galaxy, through the inverse Compton mechanism in the initial collapse phase, the cooling of protostars through the Lyα, H_2, or hyperfine transition lines of first metals, or other reprocessed radiation, and through the redistribution of orbital energy of stars in merging proto-galactic fragments (violent relaxation). The later process need not be complete

($1 < k_E \leq 2$), but it may also be possible for some galactic cores to be supervirialized ($k_E > 2$). In the well-known cooling diagram for protogalaxies (e.g., Rees & Ostriker 1977; Blumenthal *et al.* 1984; Silk 1985) the position of a galaxy is related to the degree of dissipation, which also determines its morphology. The Hubble sequence can be viewed as a dissipation sequence (Sandage 1986), and even within a given Hubble type, there may be a spread in k_E: the FP of ellipticals and bulges is almost parallel to the velocity dispersion – surface brightness plane, which is just a representation of the cooling diagram, viz., the temperature – density plane. The k_E may vary by tens of percent, even within a given Hubble type, but this variation would be very hard to detect directly, or separate from a variation in (M/L).

The parameters k_R and k_L depend on the luminosity and mass density structure of a galaxy. It is an observed fact that the surface brightness profiles of galaxies of all Hubble types, including the ellipticals, have different shapes (cf. Kent 1984, or Djorgovski 1985). The "mass types" of spirals do not correlate well with their Hubble types (Burstein 1982). The interplay between the (M/L) and velocity anisotropy makes it hard to constrain the mass distribution in ellipticals, even if the complete surface brightness and projected velocity dispersion information is available (Binney 1982). A wide range of models is possible for the disks as well, from "maximum disk", to "maximum halo" (see, e.g., Kent 1986). And even if one can start with a perfectly homologous family of galaxies, mergers and tidal encounters would modify the k_R and k_L. Some homogenization of the samples may be attempted by selecting galaxies by the shape of their surface brightness profiles: this was done with some success with the TF relation by Bothun & Mould (1987).

The parameter k_V is affected by the anisotropies of the velocity dispersion tensor, and the redistribution of kinetic energy between the ordered and chaotic motions in ellipticals, or by the shape of the rotation curve in spirals. Just like the density structures, the velocity structures of galaxies bear imprints of past mergers and tidal interactions. This is especially true for ellipticals, whose shape parameters do not correlate at all with the FP parameters, or mutually (Djorgovski & Davis 1987; Djorgovski 1987c). Two otherwise identical ellipticals with different amounts of radial anisotropy can have very different projected central velocity dispersion: Merritt (1988) shows that such effects can produce errors in (M/L) estimates (using the King-Minkowski method) of up to 150%.

Given all this, it is perhaps astonishing that there are working distance-indicator relations at all. Even if all of the observed cosmic scatter and peculiar velocities are attributed to the vartiations in K_{SR}, K_{SL}, and (M/L), the compound variations in these parameters cannot be much larger than 20%, say. Given that some fraction of the observed peculiar velocities must be gravitationally induced, the true "cosmic" variation must be even smaller. This reflects a remarkable and unexpected uniformity in the ways of manufacturing of galaxies. Possibly there are some fortuitous cancelations, but more likely, there are some as yet undiscovered regulative (feedback?) mechanisms operating in galaxy formation. Further studies of variations and scatter in distance-indicator relations may shed some light (if not mass) on this astrophysical mine.

Let us now examine some of the available data on distance indicator relations in galaxy clusters, in attempt to look for variations. This is a difficult problem, and it requires large and homogeneous sets of good-quality data. We use the set of Arecibo clusters from Bothun *et al.* (1985a) to examine the TF relation, and the set of clusters from Dressler *et al.* (1987) and Lynden-Bell *et al.* 1988, to examine the $D_n - \sigma$ relation. We can compare the slopes of relations between different clusters, but not the intercepts, which are distance-dependent. In order to check for any variation in intercepts, one needs an independent distance indicator which is at least as good, and there are none available at this time. We can, however, compare the relations derived for the cluster cores and envelopes, as the distances cancel exactly. Finally, we can test for the curvature in these relations, by plotting the slope against the redshift. Any one of these effects (variation of the slopes, intercepts, or the curvature) can generate false peculiar velocities, if an universal relation is assumed, and fitted to the data.

We use the results on 10 clusters from Lynden-Bell *et al.* (1988) in order to search for possible variations in the $D_n - \sigma$ relation. This study is mainly limited by the scarcity of clusters with more than 10 measured galaxies (only 6 clusters). The cluster properties which we use include the richness class, and the velocity dispersion, which is related to the depth of the gravitational potential of the cluster as a whole. We have used the "isophotal" diameters D_n, and the central velocity dispersions, σ, from Burstein *et al.* (1987) and Davies *et al.* (1987). The global solutions for the fundamental plane, viz., the slope and intercepts of the $D_n - \sigma$ relation, for the six more populous clusters, were taken from Lynden-Bell *et al.* (1988).

We find weak correlations of the $D_n - \sigma$ relation slope with the cluster velocity dispersion and richness class, as illustrated in Figure 1. We then divided the sample of galaxies in each cluster according to the projected radius from the cluster center, and evaluated the $D_n - \sigma$ relation for the inner and the outer

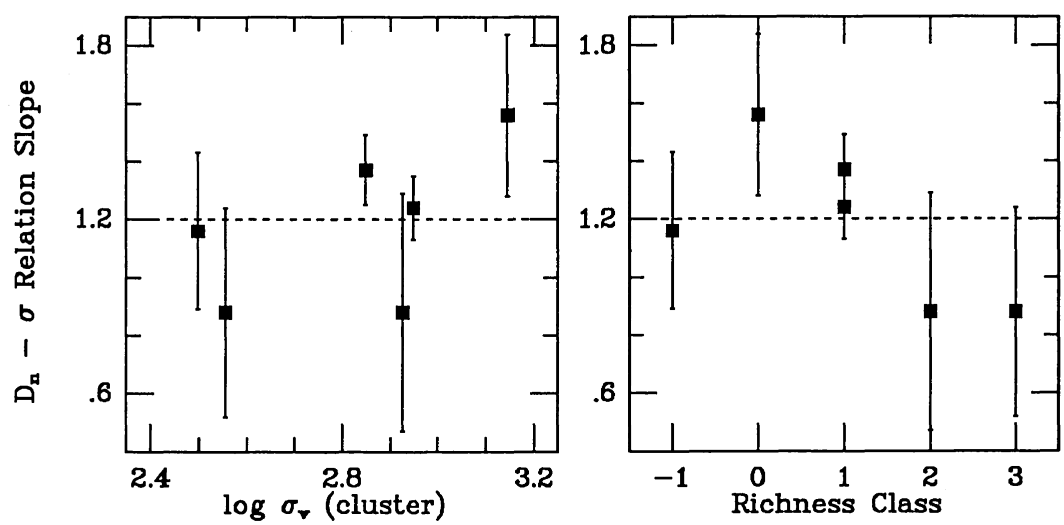

Figure 1. Dependence of the slope of $D_n - \sigma$ relation on the cluster properties, for the Lynden-Bell *et al.* (1988) clusters with more than 10 galaxies measured. The dashed lines indicate the "universal slope" proposed by those authors.

part of each cluster. We computed a minimum perpendicular distance least-squares fit, with all points weighted equally (unfortunately, there are no published error bars for D_n). Figure 2 shows the distribution of the $D_n - \sigma$ relation parameters for the inner and outer regions of the 6 clusters. The larger spread of the slopes for the inner sample is quite remarkable, and one would expect just the *opposite* effect if the outer sample was polluted by the non-cluster-members. However, the galaxy encounters should have more effect on galaxian properties in the inner regions. An alternative way to examine this effect is to correlate the *differences* in the slopes and intercepts (which are distance-independent)

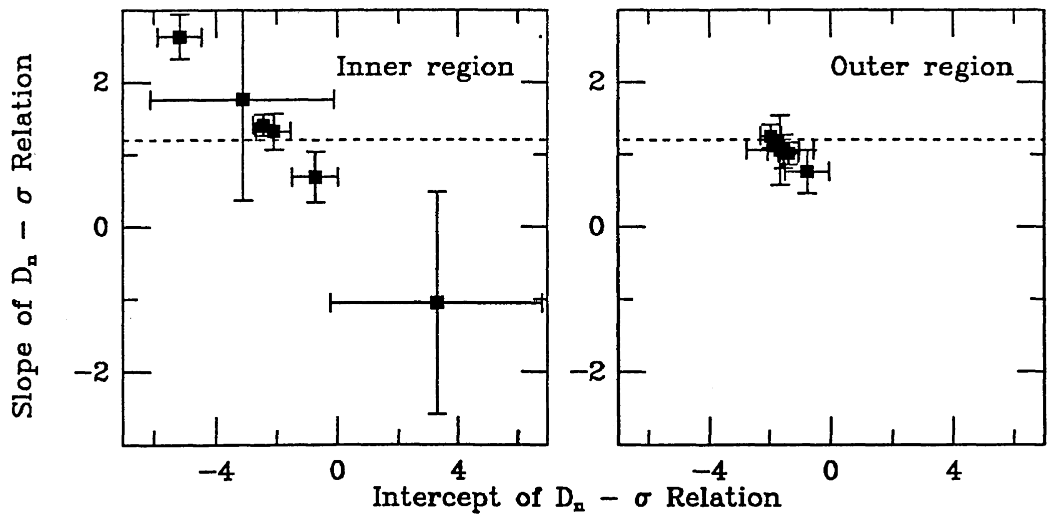

Figure 2. Parameters of the $D_n - \sigma$ relation solutions for the inner and the outer 50% of galaxies in the same 6 populous clusters as in Fig. 1.

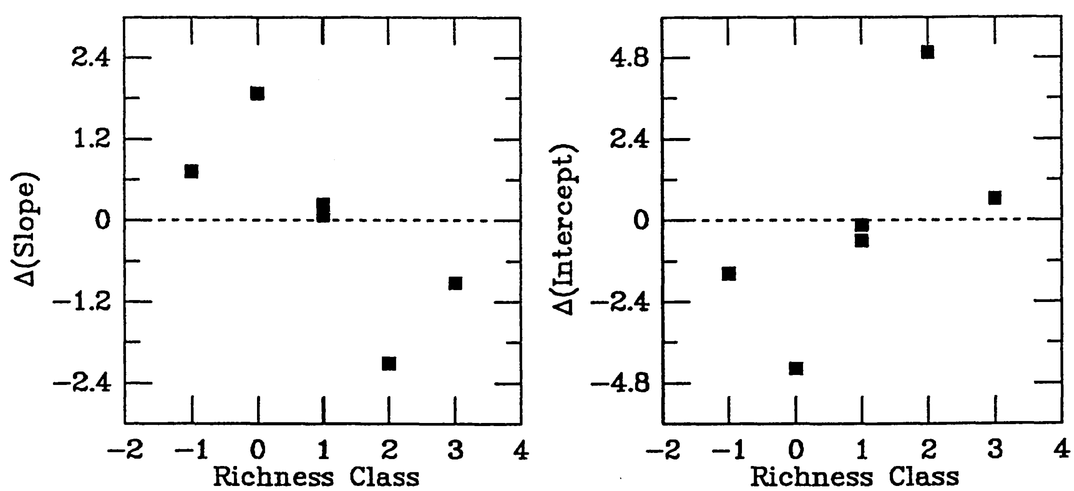

Figure 3. The differences (Inner − Outer) in $D_n - \sigma$ relation solutions for the the same 6 populous clusters as in Figs. 1 and 2, plotted against the cluster richness class.

for the inner and outer parts of each cluster with the cluster properties, as in Figure 1. The dependences of slope and intercept differences on the cluster richness class are shown in Figure 3; we find no perceptible dependence on the cluster velocity dispersion. The correlation between the intercept differences (Inner – Outer) and richness class is may be only a consequence of the slope difference variation. Any differences in intercepts, whether intrinsic or caused by the difference in slopes, would introduce a systematic error in relative distances, and thus a false component of the peculiar velocity.

To quantify these correlations, we have determined parametric and non-parametric correlation coefficients, listed below as: (Linear Regression; Spearman Rank; Kendall Rank). For the relation between the $D_n - \sigma$ slope with the cluster richness class, we obtain (–0.65; –0.79; –0.50) if all galaxies are used; (–0.66; –0.95; –0.65) if the inner 50% of galaxies in each cluster are used; and (0.17; 0.03; 0.10) for the outer 50%. For the relation between the $D_n - \sigma$ slope with the cluster velocity dispersion, we obtain (0.57; 0.48; 0.41) if all galaxies are used, and no significant correlations if we divide them in the inner and outer subsamples. For the differences in solutions between the inner and outer subsamples, computed as (Inner – Outer), we find the following: Δ(Slope) correlates with the cluster richness class as (–0.75; –0.96; –0.69), and Δ(Intercept) as (0.64; 0.81; 0.69). Again, we find no significant correlations with the cluster velocity dispersion.

To summarize, the slope of the $D_n - \sigma$ relation depends on the cluster richness class, and to a much lesser degree, on the cluster velocity dispersion. This dependence is stronger for the galaxies in the cluster cores, where the interactions dominate, and is weak or absent in the cluster envelopes.

We now consider the possible dependence of the TF relation on the morphological type. If the TF relation measures the properties of the disks only,

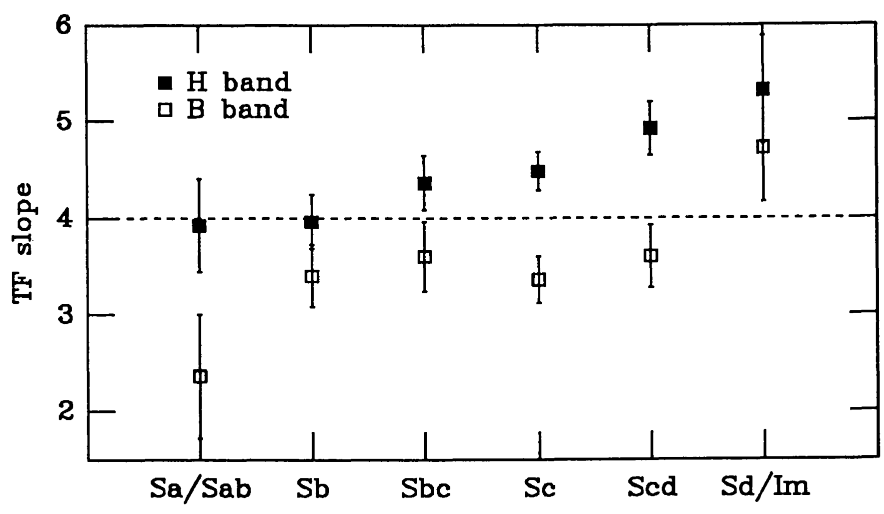

Figure 4. Dependence of the TF relation slope in the B and H bands on the Hubble type. The data were taken directly from Aaronson & Mould (1983). This dependence should translate into a dependence on environmental density, via the morphology–density relation.

a variation of the B/D ratio, the M/L, or the disk surface brightness along the Hubble sequence would induce a variation of the TF slope. In an early study, Roberts (1978) found a strong dependence of the TF relation on galaxy morphology. Then Rubin *et al.* (1982) detected a difference in TF slopes for the Sb and Sc galaxies. Aaronson and Mould (1983) claimed no significant dependence of the TF slope with the morphological type, but even their own data suggest that such dependence does exist (Figure 5). If the TF slope depends systematically on the galaxy morphology, it will then also depend on the cluster density, according to the morphology – environmental density correlation (Dressler 1980).

Kraan-Korteweg (1983) studied the *distance-independent* relation between the H I 21 cm line width and the IR surface brightness, and found a variation between different clusters. This was explored further by Bothun *et al.* (1985b), who also investigated the color – luminosity relation for galaxies in clusters, and found that it too may vary.

In order to examine the possible dependence of the TF relation on the cluster properties, we use the sample of 10 Arecibo clusters from Bothun *et al.* (1985a). A detailed description of the sample selection and the reliability of the observational parameters is found in the original paper. We performed a double linear regression TF relation fit to each of the ten clusters, by assigning a typical error of 0.04^m in H magnitude and of 20 km s^{-1} in line width as adopted from Table 3 of Bothun *et al.* (1985a). In order to guard against the pollution by non-cluster-members, we impose a relative velocity cutoff at 2.5 times the cluster velocity dispersion away from the mean cluster redshift.

We tested the dependence of the TF slope on three different environment indicators, namely, the Abell richness class, the velocity dispersion and the morphological type population. We also examine the correlation with the cluster redshift, which may be indicative of a curvature in the TF relation. The variations of the TF slope against these environment indicators are shown in Figure 4. There is a significant correlation of the TF slope with each of these variables. In our notation from above, we find the following correlation coefficients: for the dependence of the TF slope on the cluster richness class, (0.81; 0.49; 0.60) if all clusters are considered, and (0.83; 0.42; 0.62) if only the clusters with more than 10 galaxies measured are used. For the dependence on the cluster velocity dispersion, (0.69; 0.77; 0.69) for all clusters, and (0.82; 0.96; 0.90) for the clusters with more than 10 galaxies measured. We note that the correlations improve if the more reliable clusters (those with more than 10 galaxies in the sample) are used.

These correlations suggest that the TF relation has a shallower slope in rich or high-density clusters. The question now is whether this trend is intrinsic and due to a real and systematic variation of galaxian properties, or due to some bias and sample selection effects?

For the dependence of the TF slope on the cluster redshift, we obtain the following correlation coefficients: (0.71; 0.88; 0.73) for all clusters, and (0.93; 0.96; 0.90) for those with more than 10 galaxies in the sample. This effect is easily understood as due to the curvature in the TF relation, whereby one samples different portions of the luminosity function in clusters at different redshifts. This was already noticed by Aaronson *et al.* (1986), who tried a nonlinear fit to the data. The curvature of the TF relation can be produced by the non-circular motions in the spiral disks (Bottinelli *et al.* 1983), or could be partly contributed by the dependence of metallicity on disk luminosity (Bothun *et al.* 1984).

The environmental effects shown in Figure 5 might then be caused by this sample selection effect, *if* there is a good correlation between redshifts and the cluster parameters. We find a week correlation between redshift and the environmental parameters (one tends to pick richer and denser clusters at higher redshifts). However, the curvature effects cannot easily explain all of the environmental effects found above.

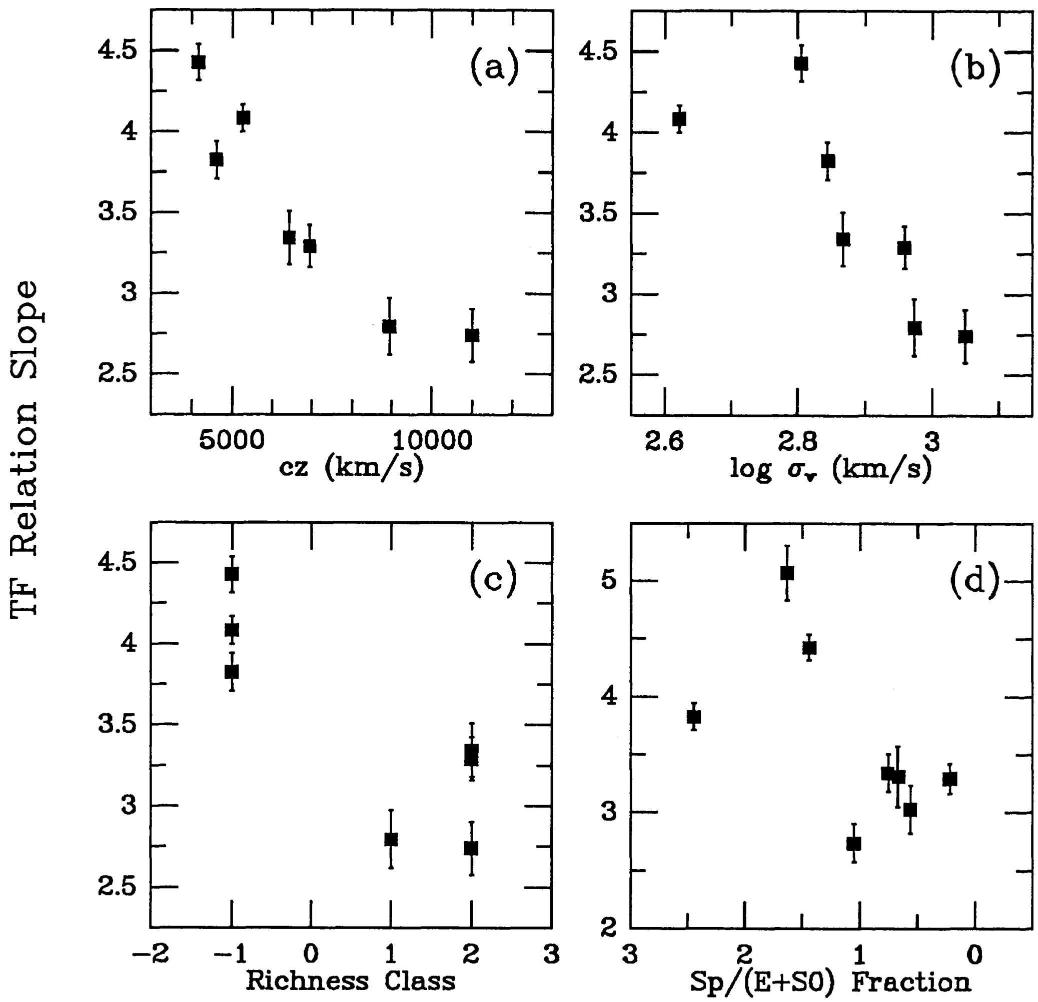

Figure 5. Dependence of the H band TF relation slope on: (a) cluster redshift, indicating a curvature in the relation; (b) cluster velocity dispersion; (c) cluster richness class; and (d) morphological composition, defined as a ratio of the fraction of spirals and the fraction of E and S0 galaxies. The data on Arecibo clusters are from Bothun *et al.* (1985a). Only the clusters with more than 10 galaxies were used in panels (a) – (c), and all clusters with available data in panel (d).

In a recent series of papers, Whitmore *et al.* (1988), Rubin *et al.* (1988), and Forbes & Whitmore (1988), explore the shapes of the rotation curves of spirals as a function of the environmental density (cluster *vs.* field, and as a function of position within a given cluster). They find a clear trend which can be most easily understood if the galaxies in denser environments have stripped or truncated halos; this trend is valid for spirals of all Hubble types and all Rubin-Burstein mass types. The implication is that the velocity widths for galaxies of identical luminosities may be systematically lower in denser environments, and thus the intercepts of the TF relation will differ as well.

The Malmquist bias effect in the TF relation has been extensively studied during the past few years (see Bottinelli *et al.* 1988 and references therein). The cluster sample we are dealing with is basically volume limited, the conventional Malmquist bias might not apply here. However as being pointed out by Teerikorpi (1986), cluster samples could suffer a similar biasing effect, due to a horizontal cut off the fainter tail of the TF relation. Such cut through TF relation with non-zero dispersion does result a slightly shallower slope, but the amount of this effect could not be too significant since the cluster sample is sufficiently deep in magnitude and the scatter in the TF relation is small (Aaronson *et al.* 1986). In fact, the sample we used here was actually selected according to the 21 cm line-width rather than the H magnitude (Bothun *et al.* 1985a), so that the incompleteness at the fainter part of the TF relation is more likely to be due to a vertical cut, and the relevant bias is to steepen the slope. Thus, this kind of bias is unlikely to produce the apparent environmental effect. Other possible sample bias such as HI signal to noise ratio and HI flux can probably be ruled out (Aaronson *et al.* 1986).

We therefore conclude tentatively that the correlations between the TF slope and the environmental parameters shown in Figure 5 are partly due to the curvature of the TF relation, and partly to either some as yet unknown sample biasing effects or a true environmental dependence. The later may well reflect the differences in formative and evolutionary processes for spiral galaxies in different environments.

In any case, we feel that further investigations of the universality of distance-indicator relations are both desirable and necessary. Their careless application can easily generate spurious effects and complicate further the measurements of the H_0. The burden of proof should be on those who claim that their empirical standard rulers are good to a couple of percent or less. On the positive side, the distance-indicator relations clearly contain valuable and perhaps unique information about the diversity of processes of galaxy formation and interaction of galaxies with their environment.

REFERENCES

Aaronson, M., and Mould, J. 1983, *Ap.J.* **265**, 1.

Aaronson, M., *et al.* 1986, *Ap.J.* **302**, 536.

Bahcall, N. 1981, *Ap.J.* **247**, 787.

Binggeli, B. 1987, in "Nearly Normal Galaxies", S. Faber (ed.), p. 195. New York: Springer.

Binney, J. 1982, in "Morphology and Dynamics of Galaxies", Saas-Fee course. Geneva: Observatoire de Geneve.

Blumenthal, G., *et al.* 1984, *Nature* **311**, 517.
Bothun, G., *et al.* 1984, *Ap.J.* **278**, 475.
Bothun, G., *et al.* 1985a, *Ap.J.Suppl.Ser.* **57**, 423.
Bothun, G., *et al.* 1985b, *Ap.J.* **291**, 586.
Bothun, G., *et al.* 1986, *Ap.J.* **308**, 510.
Bothun, G., and Mould, J. 1987, *Ap.J.* **313**, 629.
Bottinelli, L., *et al.* 1983, *Astr.Ap.* **118**, 4.
Bottinelli, L., *et al.* 1988, *Ap.J.* **328**, 4.
Burstein, D. 1982, *Ap.J.* **253**, 539.
Burstein, D., *et al.* 1987, *Ap.J.Suppl.Ser.* **64**, 601.
Davies, R., *et al.* 1987, *Ap.J.Suppl.Ser.* **64**, 581.
Davis, M., and Djorgovski, S. 1985, *Ap.J.* **299**, 15.
Davis, M., and Geller, M. 1976, *Ap.J.* **208**, 13.
Dekel, A., and Rees, M. 1987, *Nature* **326**, 455.
Djorgovski, S. 1985, Ph.D. thesis, University of California, Berkeley.
Djorgovski, S. 1987a, in "Nearly Normal Galaxies", S. Faber (ed.), p. 227. New York: Springer.
Djorgovski, S. 1987b, in "Starbursts and Galaxy Evolution", T.X. Thuan, T. Montmerle, and J. Tran Thanh Van (eds.), p. 549. Paris: Editions Frontières.
Djorgovski, S. 1987c, in "Structure and Dynamics of Elliptical Galaxies", T. de Zeeuw (ed.), p. 79. Dordrecht: Reidel.
Djorgovski, S., and Davis, M. 1986, in "Galaxy Distances and Deviations from Universal Expansion", B. Madore and R.B. Tully (eds.), p. 291. Dordrecht: Reidel.
Djorgovski, S., and Davis, M. 1987, *Ap.J.* **313**, 59.
Dressler, A. 1980, *Ap.J.* **236**, 351.
Dressler, A., *et al.* 1987, *Ap.J.* **313**, 42.
Faber, S. 1982, in "Astrophysical Cosmology", H. Bruck, G. Coyne, and M. Longair (eds.), p. 191. Vatican: Specola Vaticana.
Faber, S. 1987, in "Nearly Normal Galaxies", S. Faber (ed.), p. 175. New York: Springer.
Forbes, D., and Whitmore, B. 1988, preprint.
Giovanelli, R., Haynes, M., and Chincarini, G. 1986, *Ap.J.* **300**, 77.
Giovanelli, R., and Haynes, M. 1988, in "Towards Understanding Galaxies at Large Redshifts", R. Kron and A. Renzini (eds.), p. 133. Dordrecht: Reidel.
Gott, J.R., and Rees, M. 1975, *Astr.Ap.* **45**, 365.
Hoffman, Y., Shaham, J., and Shaviv, G. 1982, *Ap.J.* **262**, 413.
Kent, S. 1984, *Ap.J.Suppl.Ser.* **56**, 105.
Kent, S. 1986, *A.J.* **91**, 1301.
Kraan-Korteweg, R.C., 1983. *Astr.Ap.*, **125**, 109.
Lynden-Bell, D., *et al.* 1988, *Ap.J.* **326**, 16.
Merrit, D. 1988, *A.J.* **95**, 496.
Phillipps, S. 1988a, *Astr.Ap.* **194**, 77.
Phillipps, S. 1988b, *M.N.R.A.S.* **233**, 561.
Postman, M., and Geller, M. 1984, *Ap.J.* **281**, 95.
Rees, M. and Ostriker, J. 1977, *M.N.R.A.S.* **179**, 541.
Roberts, M. 1978, *A.J.* **83**, 1026.

Rubin, V., *et al.* 1982, *Ap.J.* **289**, 81.
Rubin, V., Whitmore, B., and Ford, W.K. 1988, *Ap.J.*, in press.
Sandage, A. 1986, *Astr.Ap.* **161**, 89.
Schectman, S., and Dressler, A. 1988, *Ap.J.*, in press.
Silk, J., and Norman, C. 1981, *Ap.J.* **247**, 59.
Silk, J. 1985, *Ap.J.* **297**, 9.
Silk, J. 1987, in "Dark Matter in the Universe", J. Kormendy and G. Knapp (eds.), p. 335. Dordrecht: Reidel.
Silk, J. 1988, preprint.
Teerikorpi, P. 1987, *Astr.Ap.* **173**, 39.
Tinsley, B. 1981, *M.N.R.A.S.* **194**, 63.
Whitmore, B., Forbes, D., and Rubin, V. 1988, *Ap.J.*, in press.

DISCUSSION

J. WILLICK: To what extent might the variations in TF slope with cluster richness, velocity dispersion, etc., actually be due merely to curvature in the TF relation?

S. DJORGOVSKI: That would require a good correlation between the cluster properties and the redshift, and we doubt that all of the effects described above can be explained by the curvature alone.

M. CLUTTON-BROCK: The densities of loose and compact groups differ far more from each other than do poor and rich clusters. Would it be possible to use groups to check the variation of the TF and $D_n - \sigma$ relations with environment?

S. DJORGOVSKI: A very good idea. There is not enough homogeneous data at this moment for such a check, but it would be a wortwhile experiment to do in the future, when the data are available.

D. LYNDEN-BELL: (1) The TF Coma/Virgo distance ratio agrees with the $D_n - \sigma$ distance ratio very well, only 0.015^m different. This suggests that environmental differences in Coma and Virgo cannot be very large. (2) We got very similar streaming motions from 4 different distance indicators. It is unlikely that $D_n - \sigma$ and $Mg - L_B$ relations will be environmentally affected in such a way to give the same motions. (3) The slopes of the $D_n - \sigma$ relation are dependent on the measurement accuracy. The fainter members of the large clusters are not measured to the same accuracy as the main survey.

S. DJORGOVSKI: First, let me emphasize that some of the measured peculiar velocities must be real, due to the gravitational acceleration. Those components would bear an imprint of a large-scale coherence, suggesting that the entire observed (interpreted?) velocity field is real. Our claim here is that some part of the peculiar velocity amplitudes – perhaps as much as 50% on the average – may be spurious, riding atop of the real peculiar motions. But to answer your comments in order: (1) Both TF and $D_n - \sigma$ relations depend on a very similar (astro)physics, and may vary with the environment in a similar way. I am also not sure that everybody would agree that the differential distance moduli of Virgo and Coma are that well determined. (2) No other relation is as good as TF or $D_n - \sigma$, and many of them entail similar physics, and could be affected in similar ways. We would need a *truly independent, at least as good distance indicator* to check them, and there is none such at the moment. Perhaps with the HST in Virgo... (3) We just take the slopes of the $D_n - \sigma$ from you. If they are good enough to measure the peculiar velocities, they are good enough for our tests.

G. TAMMANN: Unfortunatelly, our ways to determine galaxy distances (or only relative distances) are still so crude that if one goes into finer details, problems turn up that we still do not understand. For instance, one expects relative distances to Coma and Virgo to be particularly well determined. Yet the $D_n - \sigma$ method yields $\Delta(m - M)_{Coma-Virgo} = 3.62$ (Lynden-Bell, priv.comm.), and the TF method requires a best value of 3.8 – 4.0 (Bottinelli *et al.* 1988, *Astr.Ap.* **196**, 17; Kraan-Korteweg *et al.* 1988, *Ap.J.*, in press). Moreover, Aaronson *et al.* (1986, *Ap.J.* **302**, 536) claimed from TF data to see our MWB motion reflected in the motion of distant clusters, while Kraan-Korteweg *et al.* (1988) did not see a trace of it from the same data. If you find here several subtle effects in the data on the 11 clusters, this does therefore not reflect any physics, but possibly only the enormous problems to define fair samples.

S. DJORGOVSKI: Certainly, the selection effects are at least as important as any physical variations in distance-indicator relations which may be present, and the trends which we observe are probably reflecting a combination of causes. Ideally, we would like large and homogeneous data samples with well-understood selection procedures, in order to test the environmental effects, but they are hard to get. We used the best data we could find, and our investigation is clearly very preliminary.

J. MOULD: I agree that in analysing data by the $D_n - \sigma$ and TF techniques, one has a choice of concluding that the galaxies are peculiar, or that the velocities are peculiar. However, there is one peculiar velocity that we can be fairly sure of, and that is the 600 km s^{-1} velocity of the Local Group relative to the MWB. In our analysis of the Arecibo clusters, we recovered that motion to ± 200 km s^{-1}. This confirmation, together with the economy of hypotheses suggests that this is the route to take.

S. DJORGOVSKI: It is my impression that explaining the MWB vector is a tricky problem, and a highly model-dependent one (e.g., the IRAS dipole controversy, etc.). Some of the Local Group motion is probably easily explained, but I doubt that the local acceleration field is so well known as to claim the complete success. The result you quote may be partly fortuitous. I don't think that the universality of the TF relation is an economical hypothesis, it is perhaps an insufficiently justified one.

R. NOLTHENIUS: I would worry that a significant part of the apparent flattening of the Tully-Fisher relation slope with spiral cluster richness is due to contamination. Spirals are notoriously difficult to group accurately, since they inhabit lower density regions, and too liberal a velocity linkage cutoff will produce severe contamination.

S. DJORGOVSKI: We've used Bothun's cluster identifications and cut out anything beyond 2σ.