THE ASTROPHYSICAL JOURNAL, 343:18–25, 1989 August 1

ON SYSTEMATIC ERRORS IN DISTANCE ESTIMATES OF THE VIRGO CLUSTER AND THE INTRINSIC SCATTER IN THE TULLY-FISHER RELATION

DAVID BURSTEIN
Department of Physics, Arizona State University; and Institute of Astronomy, Cambridge, England

AND

SOMAK RAYCHAUDHURY
Institute of Astronomy, Cambridge, England
Received 1988 December 8; accepted 1989 January 17

ABSTRACT

Recent estimates of the amplitude of scatter in the Tully-Fisher relation and the related question of distance to the Virgo cluster are critically examined. The scatter of 0.7 mag in the Tully-Fisher relation found by Kraan-Korteweg, Cameron, and Tammann is found to be primarily observational in origin, the combination of line-of-sight effects within their 121 galaxy sample and the use of older, poorly determined magnitudes. The true scatter in the Tully-Fisher relation is less than 0.4 mag, as found by Pierce and Tully. The assumptions that both Pierce and Tully and Kraan-Korteweg, Cameron, and Tammann used in their separate determinations of the distance to the Virgo cluster are applied to the same combined sample of 131 galaxies, defined to be consistent with the formalism of Kraan-Korteweg, Cameron, and Tammann. The use of different subsets of calibrator galaxies by the two studies permits both distance estimates to be consistent with these data, despite differing in predicted distance modulus by 0.6 mag! In the absence of a general agreement on inclination corrections to magnitudes, diameters, and rotation velocities, the choice of calibrator galaxies and the distances to them and the reliability of observed data, no agreement can be reached on the distance of the Virgo cluster as derived from the Tully-Fisher relation for spiral galaxies.

Subject headings: cosmology — galaxies: clustering — galaxies: distances

I. INTRODUCTION

As the nearest populous cluster of galaxies, the Virgo cluster is perhaps the most-studied in the sky. Yet estimates of its distance modulus still differ by at least 0.6 mag, as evident from the two recent analyses of Pierce and Tully (1988, hereafter PT) and of Kraan-Korteweg, Cameron, and Tammann (1988, hereafter KCT). This disagreement persists despite the fact that both studies employ the same method to estimate distance—the Tully-Fisher relation for spiral galaxies (Tully and Fisher 1977).

These two studies also differ markedly in their estimates of intrinsic scatter (i.e., wavelength-independent) in the Tully-Fisher relation, as derived from their respective analyses. PT find that the intrinsic scatter is less than 0.3 mag in the I passband, based on their study of 26 galaxies in the Virgo cluster and 26 galaxies in the Ursa Major cluster. In contrast, KCT conclude that the intrinsic scatter is 0.7 mag in both the B and the near-infrared H passbands, based on a study of 121 Virgo cluster galaxies. They claim that estimates of smaller scatter (such as that of PT) are biased due to the exclusion of intrinsically fainter galaxies having rotation velocities comparable to those of the brighter galaxies. KCT further state that this bias is the source of the smaller distance modulus of the Virgo cluster that was found by Aaronson *et al.* (1986).

A large intrinsic scatter in the Tully-Fisher relation, independent of wavelength, would make interpretation of the overall peculiar velocity field near the Sun very difficult (Faber and Burstein 1988). It is also inconsistent with other recent analyses of the intrinsic width of the Tully-Fisher relation (Burstein *et al.* 1988; Faber and Burstein 1989).

It is therefore of interest to reexamine critically the claim of KCT regarding the sources of scatter in the Tully-Fisher relation and, consequently, the sources of error in current estimates of the distance to the Virgo cluster. The existence of line-of-sight depth effects in the Virgo galaxy sample of KCT is investigated in § II. The sources of scatter in the blue Tully-Fisher relation for this sample are explored in § III, together with the origin of the widely different distance estimates to the Virgo cluster obtained by KCT and by PT. The systematic differences that exist in the current versions of the blue Tully-Fisher relation are delineated in § IV, through a comparison of the data of KCT with those of PT for galaxies in common to the two samples. Finally, the overall effect of these systematic errors on the determination of the distance to the Virgo cluster is discussed in § V.

II. LINE-OF-SIGHT DEPTH EFFECTS TOWARD THE VIRGO CLUSTER

Consider the following straightforward test for line-of-sight effects in any prospective sample of Virgo cluster galaxies: is the scatter in the Tully-Fisher relation correlated with radial velocity? This test makes no assumption either about the slope and zero point of the Tully-Fisher relation, or about the kind of peculiar velocity field that exists around the Virgo cluster. As a result, the outcome of this test is not predictable *a priori*: If line-of-sight confusion exists *and* the peculiar velocities generated by the Virgo cluster are small compared to the range of radial velocities, then the scatter in the Tully-Fisher relation will be correlated with the radial velocities of the galaxies. If, on the other hand, the peculiar velocities generated by the Virgo cluster are large compared to the range of radial velocities, no such correlation would exist (i.e., imagine what one would expect if the Milky Way were situated within the infalling region, close to the Virgo cluster center). The same would also be true if all of the galaxies were bona fide members of the Virgo cluster (as implicitly assumed by KCT).

TABLE 1

MEDIAN VALUES OF $B_T^{0,i}$ AND log (ΔV_{20}) IN INTERVALS OF log (ΔV_{20}) UNDER THREE DIFFERENT ASSUMPTIONS

	KCT SAMPLE ALONE FOR 121 GALAXIES			KCT + PT SAMPLE FOR 131 GALAXIES			PT SAMPLE ALONE FOR 26 GALAXIES		
RANGE IN log ΔV_{20}	Median[a] $B_T^{0,i}$	log ΔV_{20}[a]	N	Median[a] $B_T^{0,i}$	log ΔV_{20}[a]	N	Median[a] $B_T^{0,i}$	log ΔV_{20}[a]	N
< 1.8	16.30	1.75	7	16.30	1.75	7	...	...	...
	0.24	0.026		0.24	0.026				
1.8–1.89	16.25	1.87	8	16.25	1.87	8	...	...	...
	0.72	0.021		0.72	0.021				
1.9–1.99	15.20	1.93	9	15.20	1.93	9	...	...	...
	0.56	0.024		0.56	0.024				
2.0–2.09	14.85	2.05	12	14.80	2.05	13	14.28	2.05	1
	0.60	0.027		0.59	0.025		...	...	
2.1–2.19	14.76	2.15	19	14.76	2.15	19	...	...	...
	0.37	0.023		0.37	0.023				
2.2–2.29	13.98	2.24	16	13.98	2.24	16	14.40	2.20	1
	0.47	0.024		0.47	0.024		...	...	...
2.3–2.39	13.07	2.35	12	13.07	2.35	12	...	...	...
	0.72	0.016		0.72	0.016				
2.4–2.49	12.02	2.45	17	12.00	2.46	19	11.79	2.475	6
	0.63	0.030		0.61	0.030		0.25	0.015	
2.5–2.59	11.68	2.555	12	11.67	2.535	14	11.58	2.54	7
	0.69	0.037		0.69	0.031		0.50	0.033	
>2.6	10.68	2.66	9	10.14	2.68	13	10.05	2.68	11
	0.73	0.037		0.61	0.048		0.41	0.054	

[a] Median $B_T^{0,i}$ and log ΔV_{20} values appear on first line; errors for each of these quantities are given on second line.

The primary KCT sample of 121 galaxies was divided into 10 bins of H I profile rotation velocity widths, log ΔV_{20}, as defined in Table 1, where ΔV_{20} is the H I profile rotation velocity width of a galaxy measured at the level of 20% of peak flux (KCT). The size of these bins was a compromise between the desire for bins of narrow width and the need to include a reasonable number of galaxies in each bin. The median value of apparent magnitude in each bin, along with the median value of log ΔV_{20} for that bin, are tabulated in Table 1. Errors in the median values are represented by the mean absolute deviation from the median in each bin. In accordance with the analysis of KCT, the seven Sa galaxies in their original sample are not included in the present analysis, and the KCT values of log ΔV_{20} and fully corrected $B_T^{0,i}$ magnitude are used for the rest.

Figure 1 plots the blue Tully-Fisher relation for these 121 galaxies, together with the median values of apparent magnitude and log ΔV_{20} in each log ΔV_{20} bin. A line is also shown, representing the linear Tully-Fisher relation used by KCT in their analysis. The median values of $B_T^{0,i}$ are in good agreement with the slope and zero point of the blue Tully-Fisher relation as defined by KCT, although the median points appear to define a somewhat steeper slope for galaxies having values of log $\Delta V_{20} > 2.1$ (see § III).

The residuals of apparent magnitude relative to the median magnitude in each log ΔV_{20} bin ($B_T^{0,i} - B_{T,\mathrm{med}}$) are plotted in Figure 2*a* versus radial velocity (corrected to the Local Group rest frame by $+300 \sin l \cos b$; de Vaucouleurs, de Vaucouleurs, and Corwin 1976) for 61 galaxies of morphological types Sab–Sd, and in Figure 2*b* for 60 galaxies of types Sdm–Im. It is apparent that there is a correlation of $B_T^{0,i} - B_{T,\mathrm{med}}$ with radial velocity for Sab–Sd galaxies in the sense of a line-of-sight effect: Galaxies with lower radial velocities are brighter on average; galaxies with higher radial velocities are fainter on average. The slope of the best-fit straight line in Figure 2*a* is 0.3 mag (1000 km $\mathrm{s}^{-1})^{-1}$. No such depth effect is apparent for galaxies of type Sdm and later [Fig. 2*b*; the slope is -0.04 mag (1000 km $\mathrm{s}^{-1})^{-1}$].

The velocity dispersion of true Virgo cluster members will produce a range in radial velocity that will have no correlation with ($B_T^{0,i} - B_{T,\mathrm{med}}$). To identify obvious Virgo members from the KCT sample, we use the 23 galaxies in common between KCT and PT, and take advantage of the kinematical analysis of PT that places 17 of these galaxies within the core of the Virgo cluster. Figure 2*c* shows that the values of ($B_T^{0,i} - B_{T,\mathrm{med}}$) for these 17 galaxies (15 of which are of types Sab–Sd), as calculated from the KCT data, show no correlation with radial velocity [the slope is 0.07 mag (1000 km $\mathrm{s}^{-1})^{-1}$].

The relationship between ($B_T^{0,i} - B_{T,\mathrm{med}}$) and radial velocity for the remaining 46 Sab–Sd galaxies in the KCT sample shows a more significant correlation [a slope of 0.53 mag (1000 km $\mathrm{s}^{-1})^{-1}$] with a scatter of ± 0.77 mag (Fig. 2*d*), corresponding to a variation in distance of up to 43% for a Virgo cluster distance modulus of 31.6.

Of the galaxies producing the correlation between ($B_T^{0,i} - B_{T,\mathrm{med}}$) and radial velocity for the KCT sample, two are well known foreground candidates from previous studies (N4192 and N4569; see Tully and Shaya 1984). This analysis of the KCT sample also supports the view that the galaxies in the well known "low-velocity" cloud in the direction of Virgo are in the foreground of the Virgo cluster, as well as the view that some of the galaxies with high radial velocities relative to Virgo are in the background of the cluster (Tully and Shaya 1984).

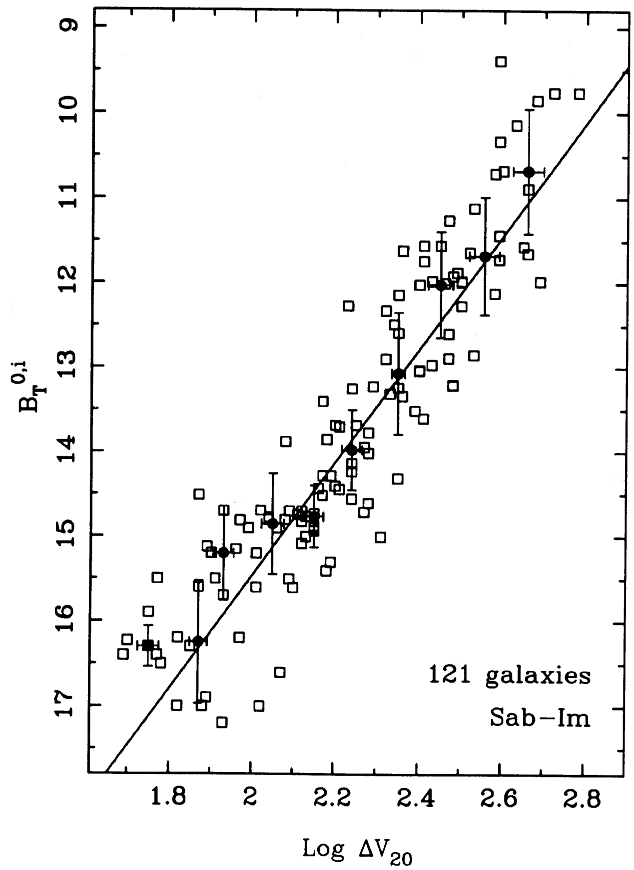

FIG. 1.—The blue Tully-Fisher relation as defined by the 121 galaxies (*open squares*) in the Virgo cluster sample of KCT. The magnitude $B_T^{0,i}$ and rotation width log ΔV_{20} are fully corrected for inclination and galactic extinction as given by KCT. The line drawn represents the assumed Tully-Fisher relation used by KCT in their analysis. Median values of $B_T^{0,i}$ and log ΔV_{20} in bins of log ΔV_{20} are plotted as closed circles, with errors as noted.

III. DISTANCE TO THE VIRGO CLUSTER AND INTRINSIC SCATTER IN THE TULLY-FISHER RELATION

The Virgo cluster sample of PT is similar to that of Aaronson *et al.* (1982), with which KCT compares both the zero point and the width of the Tully-Fisher relation derived from their much larger sample. In particular, PT derive a distance modulus for Virgo of 30.98 from the blue Tully-Fisher relation, which is very similar to the value of 30.82 derived by Aaronson *et al.* (1986). In addition to the 23 galaxies in common between the PT and KCT samples, all 11 of the remaining galaxies in the PT sample are listed in the Virgo Cluster Catalog (Binggeli, Sandage, and Tammann 1985) and have fully corrected values of $B_T^{0,i}$ given in the galaxy catalog of Kraan-Korteweg (1986).

These 11 galaxies were apparently excluded from the KCT sample due to low inclinations given in the Kraan-Korteweg catalog. However, as PT have accurately redetermined these inclinations from new CCD photometry, we chose to include them in the present analysis, albeit separately identified from the other galaxies. Values of log ΔV_{20} that are on the same system as used by KCT (see § IV) were derived from the values of rotation velocity width and inclination given by PT. The correction for inclination is, as quoted by KCT, according to the prescription of Aaronson *et al.* (1982). The KCT-compatible data for these 11 galaxies are given in Table 2.

The blue Tully-Fisher relation for the 121 galaxies of KCT and nine of the 11 additional galaxies from PT (Table 2) is plotted in Figure 3. The four different subsets of data are indicated as different symbols: 99 KCT galaxies that have no correspondence to the PT sample (*open squares*); 17 galaxies in common between KCT and PT and placed by PT in the Virgo cluster core (*filled circles*); five galaxies in common between KCT and PT but classified by PT as nonmembers of the Virgo cluster (*open circles*; one galaxy, N4698, was excluded as a nonmember from both samples); and the nine PT galaxies that have no correspondence with KCT, are members of the Virgo Cluster Catalog and are listed as Virgo cluster members by PT (*six-sided stars*; two galaxies, I769 and N4451 are excluded).

Superposed on the data plotted in Figure 3 are four lines:

a) a solid line, representing the relationship $B_T^{0,i} = 6.69 * \log \Delta V_{20} - 2.77 + 31.61$, which is derived from the distance modulus of 31.61 to the Virgo cluster derived by KCT from their assumed distances to 13 calibrator galaxies, combined with the slope of the blue Tully-Fisher relationship derived from these calibrators by KCT.

b) a dotted line, joining the median values of $B_T^{0,i}$ and log ΔV_{20} calculated from the PT "Virgo core" sample alone *but* using KCT data (see Table 1), in three bins of log ΔV_{20} (2.4–2.49, 2.5–2.59, ≥ 2.6);

c) a dashed line, joining the median values of $B_T^{0,i}$ and log ΔV_{20} calculated from the combined samples of KCT + PT for the above log ΔV_{20} bins, as well as for the interval 2.3–2.39; and

d) a solid line connecting three filled triangles, representing those values of $B_T^{0,i}$ and log ΔV_{20} that *would be observed* for the three calibrator galaxies of PT (N224, N598, and N2403) *if* (i) the KCT values of apparent magnitude and log ΔV_{20} are used for the calibrator galaxies; (ii) The distances to these three galaxies are as assumed by PT, and (iii) the Virgo cluster is placed at a distance modulus of 30.98 as determined by PT.

Condition i is required to ensure that the data for these three calibrator galaxies are on the same system as used by KCT (see § IV). Condition ii is necessary because the distance moduli used by KCT and PT for these three calibrator galaxies differ in the sense $(m - M)(\mathrm{PT}) - (m - M)(\mathrm{KCT}) = +0.2$ for N224, -0.2 for N598, and -0.3 for N2403. The differences in the manner in which the data for these three galaxies are handled by KCT and by PT are summarized in Table 3. [Note that PT use a value of Galactic extinction of $A_B = 0.17$ for M31. As explained in Burstein and Heiles (1984), this value is too low, and a value of 0.31 mag is preferred.]

With these three conditions applied, the Virgo distance modulus predictions of PT and KCT can be directly compared on the terms as defined by the original two papers, *but relative to the same, self-consistent data set as defined by KCT alone.* Inspection of Figure 3 demonstrates the following.

1. The blue Tully-Fisher relationship defined by median values of $B_T^{0,i}$ and log ΔV_{20} for the combined KCT + PT sample has a zero-point that is nearly identical to that for the PT sample alone, *in the range of* log ΔV_{20} *covered by the PT sample.* This contradicts the claim of KCT that the zero point of the blue Tully-Fisher relation defined by Virgo cluster galaxies changes significantly when they increase the number of galaxies in the sample. This close agreement in zero point also means that systematic differences in the handling of magni-

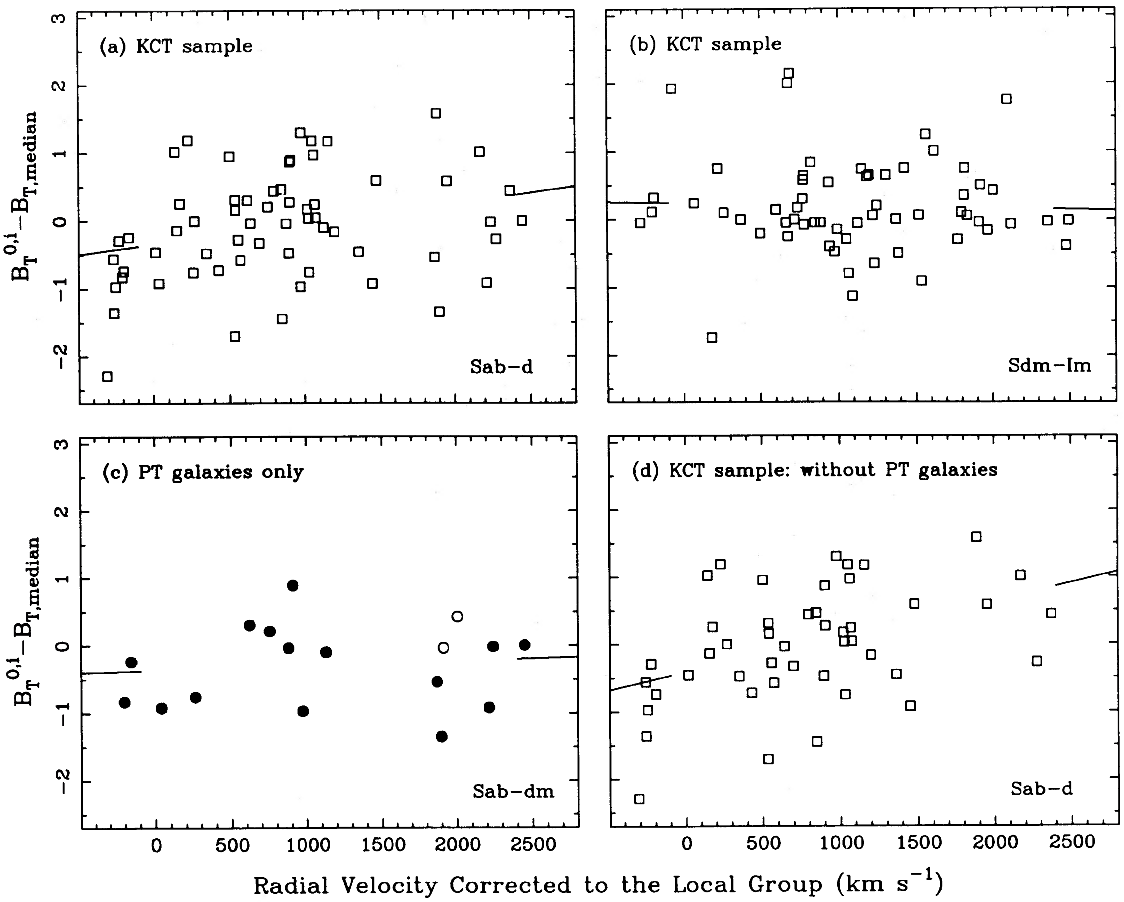

FIG. 2.—The residuals of $B_T^{0,i}$ magnitude from the median magnitude within each interval of log ΔV_{20} ($B_{T,\mathrm{median}}$), plotted versus the radial velocities of the galaxies in the Virgo cluster sample of KCT (121 galaxies, corrected to the Local Group motion by $+300 \sin l \cos b$), for the following samples: (*a*) 61 Sab–Sd galaxies; (*b*) 60 Sm–Im galaxies; (*c*) 17 galaxies (15 Sab–Sd, filled circles; 2 Sm filled circles) in common between KCT and PT which PT place in the Virgo cluster core; (*d*) the remaining 46 Sab–Sd galaxies of KCT after the subset of PT galaxies is removed. The existence of a correlation in this diagram indicates that there is significant line-of-sight contamination of the sample. The best-fit straight line slopes are indicated by the line segments at the corners of each plot.

tudes and rotation velocities cannot be the source of the 0.6 mag difference in Virgo cluster distance moduli derived by these two groups (as claimed by Fouque *et al.* 1989).

2. The scatter in the blue Tully-Fisher relation is seen to be the same or smaller for the 32 galaxies in our subset of the PT sample (*filled circles + open circles + six-sided stars*) compared to the scatter defined by those KCT galaxies not in common with PT (*open squares*). This is true even for the nine more face-on PT galaxies that were not included in the KCT sample (*six-sided stars*). Pierce and Tully, using their own data set, obtain a scatter of 0.5 mag in $B_T^{0,i}$ for 31 of these galaxies, significantly less than the scatter of 0.7 mag that is obtained by KCT. Even then, PT ascribe much of the remaining scatter to an intrinsic spread in distance among these galaxies, a plausible argument owing to the fact that H I-rich spiral galaxies tend to avoid the centers of clusters (Giovanelli and Haynes 1983).

From this comparison one concludes that the larger scatter in the Tully-Fisher relation found by KCT is almost certainly the result of observational error and line-of-sight depth effects, rather than due to a large intrinsic width of the Tully-Fisher relation. Possible sources of observational error in the KCT sample are discussed further in § IV. The present analysis of the KCT data is consistent with the conclusion of Pierce and Tully that, for well observed galaxies, the blue Tully-Fisher relation has an intrinsic scatter of less than 0.4 mag.

3. Remarkably, both the Virgo distance modulus of 31.61 derived by KCT from their 13 calibrator galaxies *and* the Virgo distance modulus of 30.98 derived by PT from their more restricted sample of 26 galaxies are consistent with the KCT data. Figure 3 was constructed in the manner shown specifically to illustrate how such an unusual circumstance could arise. Pierce and Tully use only three galaxies to calibrate their distance to Virgo—N224, N598, and N2403—all with values of log $\Delta V_{20} > 2.4$ (on the KCT system). In contrast, Kraan-Korteweg, Cameron, and Tammann use 13 galaxies to calibrate their relationship, eight of which have log $\Delta V_{20} < 2.4$. The linear slope of the calibration line used by KCT fits their relationship for fainter galaxies, but predicts too faint a magnitude for galaxies with $B_T^{0,i} < 11$. In contrast, the data for the three PT calibrator galaxies, with the distances to them as assumed by PT, fitted well the Tully-Fisher relationship defined by these brighter galaxies. Moreover, even if the KCT distances to these three calibrator galaxies are used, the dis-

TABLE 2

KCT–Compatible Data for the Galaxies in PT not in KCT, as Determined from Kraan-Korteweg (1986)

Galaxy Name	Kraan-Korteweg[a] B_T[b]	Kraan-Korteweg[a] Cor[c]	Kraan-Korteweg[a] $B_T^{0,i}$[c]	PT[e] i[f]	PT[e] w_{20}[g]	KCT-compatible w_{20c}[h]	KCT-compatible $\log \Delta V_{20}$[i]
I769	13.17	0.41	12.76	49	261	343	2.54
N4189	12.51	0.33	12.18	55	286	347	2.54
N4254	10.37	0.32	10.05	29	268	548	2.74
N4321	10.13	0.32	9.81	25	273	643	2.81
I3356	14.49	0.21	14.28	53	89	111	2.05
N4451	13.35	0.41	12.94	51	236	294	2.47
N4548	10.98	0.55	10.43	35	261	454	2.66
N4571	11.81	0.32	11.49	35	175	305	2.48
N4579	10.59	0.55	10.04	42	377	561	2.75
N4647	12.02	0.36	11.66	40	198	306	2.49
N4689	11.58	0.33	11.25	39	205	324	2.51

[a] Data as given by Kraan-Korteweg 1986, on a system consistent with that used by KCT.
[b] B_T: observed total blue magnitude.
[c] Cor., total corrections to blue magnitude, inclusive of galactic extinction and inclination.
[d] $B_T^{0,i}$: fully corrected blue magnitude.
[e] Data as given by PT.
[f] i: inclination of galaxy to line of sight, in degrees.
[g] w_{20}, observed H I profile velocity width defined at the 20% of maximum level.
[h] w_{20c}, inclination-corrected value of w_{20}, calculated from the formula given by Aaronson *et al.* 1982, in accordance with KCT.
[i] $\log w_{20c}$, defined here as $\log \Delta V_{20}$.

tance modulus of PT will still have fitted these calibrators to the Virgo data better than the linear relation defined by KCT.

It is obvious from this comparison that the distance modulus to the Virgo cluster, as currently obtained by the blue Tully-Fisher relationship, is inherently ambiguous: galaxies with high rotation velocities give a consistent value for the distance modulus that is ~ 0.5 mag smaller than galaxies with low rotation velocities. Pierce and Tully observed primarily brighter galaxies with high rotation velocities and, hence, derived a smaller distance modulus. Kraan-Korteweg, Cameron, and Tammann observed primarily fainter galaxies with low rotation velocities and derived a larger distance modulus.

In summary of this section, it has been shown that (1) the large scatter in the blue Tully-Fisher relation of KCT, as defined by their Virgo cluster sample, is observational in origin and not intrinsic to the Tully-Fisher relation and (2) the distance modulus of the Virgo cluster that one derives from the KCT sample differs between galaxies with high rotation velocities and galaxies with low rotation velocities. It is primarily this fact that leads KCT and PT to derive distance moduli to the Virgo cluster that differ by 0.6 mag.

TABLE 3

Comparison between Data of PT and KCT for N224, N598, and N2403

Data Compared	Source	N224	N598	N2403
Observed B_T	PT	4.63	6.45	8.81
	KCT	4.38	6.26	8.89
Galactic extinction Plus inclination correction to B_T: ...	PT	0.80	0.34	0.39
	KCT	1.27	0.57	0.60
$B_T^{0,i}$, fully corrected blue magnitude	PT	3.83	6.11	8.42
	KCT	3.12	5.69	8.29
$\log \Delta V_{20}$, rotation velocity widths corrected for inclination:	PT	2.706	2.305	2.412
	KCT	2.75	2.40	2.48
Assumed distance modulus $m - M$;	PT	24.4	24.2	27.5
	KCT	24.2	24.4	27.8

IV. SYSTEMATIC DIFFERENCES BETWEEN PT AND KCT DATA SETS

The Virgo cluster data sets of PT and KCT differ in several important respects:

1. PT use new CCD photometry to determine self-consistent magnitudes and colors. KCT use the magnitudes of the Virgo Cluster Catalog (Binggeli, Sandage, and Tammann 1985), which combine data having a wide range in accuracy and compatibility in zero point. Figure 4 plots the difference in observed values of B_T (i.e., without any extinction corrections), in the sense PT $-$ KCT, as a function of $\log \Delta V_{20}$ as defined by KCT for 32 galaxies in common. PT magnitudes are consistently fainter than KCT magnitudes by ~ 0.1 mag with a scatter of ~ 0.1 mag for galaxies with $\log \Delta V_{20} > 2.45$. PT magnitudes tend to become progressively fainter relative to KCT magnitudes with decreasing rotation velocities, with differences of up to 1.0 mag.

2. The inclination corrections for magnitude and diameter used by PT follow the prescriptions of Tully and Fouque (1985), which are generally in accord with those adopted in the Second Reference Catalog of Bright Galaxies (de Vaucouleurs, de Vaucouleurs, and Corwin 1976, hereafter RC2). KCT use the inclination corrections of the Revised Shapley-Ames catalog (Sandage and Tammann 1981), which follow the precepts of Holmberg (1958). These two methods can differ in zero point by up to 0.4 mag for the most inclined galaxies, with the PT corrections being smaller than those of KCT.

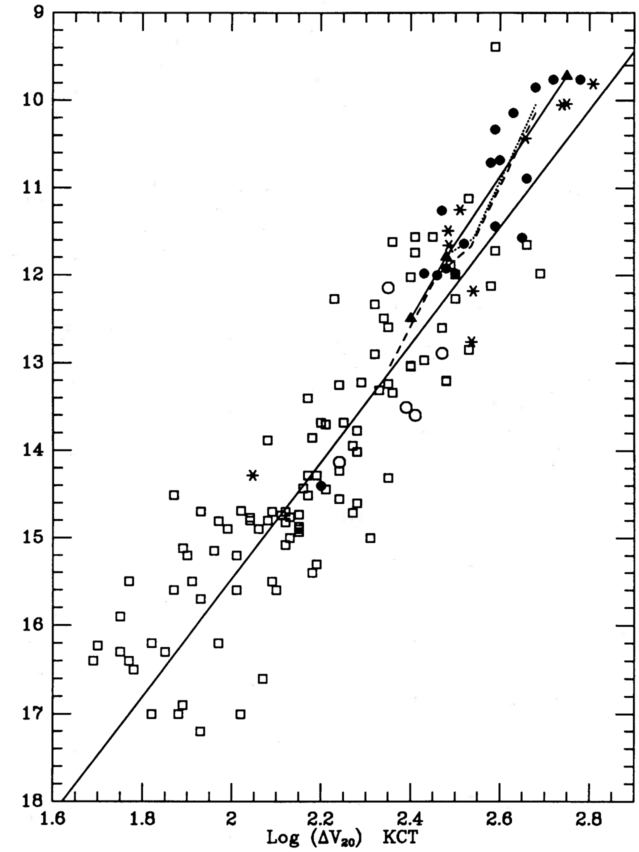

FIG. 3.—The blue Tully-Fisher relation for the combined Virgo cluster sample of KCT and PT (131 galaxies; 121 from KCT and 10 from PT), but defined only by data compatible with the analysis of KCT. Of these, 99 galaxies are in the KCT sample only (*open squares*); 17 galaxies are in both the KCT and PT samples, and are placed in the Virgo cluster core by PT (*filled circles*): five galaxies are in both the KCT and PT samples but are classified by PT as nonmembers (*open circles*); nine galaxies are only in the PT sample, but are members of the Virgo cluster as defined by both PT and by the Virgo Cluster Catalog (*six-sided stars*). The long straight line is the blue Tully-Fisher relationship as defined by KCT at the distance modulus of 31.61 derived by KCT for the Virgo cluster. The dotted line connects the median values of $B_T^{0,i}$ and log ΔV_{20} only for the PT sample of Virgo cluster core members. The dashed line connects the median values of $B_T^{0,i}$ and log ΔV_{20} for the combined KCT + PT sample, in the range of log ΔV_{20} containing almost all of the PT galaxies. Filled triangles connected by a line represent the apparent magnitudes of N224, N598, and N2403 if they had KCT apparent magnitudes, PT actual distances, and were shifted to the PT Virgo distance modulus of 30.98. (Error bars are omitted from these lines in the interest of clarity.) Note that both PT and KCT calibrations are consistent with this data set, even though they differ in predicted distance modulus of Virgo by 0.6 mag!

3. PT follow the precepts of Bottinelli *et al.* (1984) and attempt to correct the observed rotation velocities of the galaxies for estimates of nonrotational motions. KCT follow the example of Aaronson *et al.* (1982) and use the rotation velocities as observed.

These differences in the treatment of the data result in markedly different final values for the same galaxies: values of $B_T^{0,i}$ of KCT are, on average, 0.4 mag brighter than those of PT with considerable scatter, while values of log ΔV_{20} of KCT average 0.065 dex larger than those of PT. Ironically, the net effect of these systematic differences is small, as KCT have both brighter magnitudes and larger corrected rotation velocities. If one assumes an average slope of the Tully-Fisher relation of 6.75 (in accord with both KCT and PT), the net zero point shift in the Tully-Fisher relation (KCT − PT) is only $(-0.4 + 0.065 \times 6.75) = 0.04$ mag.

These systematic differences in corrections for inclination also apply to data for the three calibrator galaxies in common between the two data sets. The differences in observed values of B_T used for N224, N598, and N2403 are plotted versus log ΔV_{20} (KCT–compatible) in Figure 4. It is of special note that the *observed* B_T magnitude of N224 determined by PT ($B_T = 4.63$) is 0.25 mag fainter than that used by KCT and the RSA ($B_T = 4.38$). This substantial difference was not noted by PT in their paper, although this fainter magnitude is clearly implied by the data in their Table 4, whereas the value of 4.38 for the blue magnitude of N224 is that value given in the RC2 and has been accepted for over a decade.

V. DISCUSSION

Taken at face value, the separate analyses of Kraan-Korteweg, Cameron, and Tammann on the one hand, and Pierce and Tully on the other hand, would appear to yield estimates of the distance modulus of the Virgo cluster that differ by over two sigma *from the same, self-consistent data set*. Is there an inherent ambiguity in the use of the blue Tully-Fisher relation to determine the distance to the Virgo cluster, or is it possible that more subtle combinations of systematic errors still conspire to obfuscate? The present analysis can identify at least five kinds of systematic errors that could combine to produce the present confusing situation:

a) Systematic Errors in the Observed Blue Magnitudes of the Fainter Galaxies in the Virgo Cluster

Many of the brighter Virgo galaxies have values of B_T determined either from photoelectric observations, or by Holmberg (1958). However, most of the galaxies in the KCT sample have magnitudes that were either estimated by de Vaucouleurs and Pence (1979) from older photographic data (i.e., that of Ames 1930 and Zwicky, Herzog, and Wild 1960–3) or by Binggeli, Sandage, and Tammann (1985) from their photographic plates. It is therefore probable that the B_T data used by KCT for the brighter galaxies in their sample are of much better quality than those used for the fainter galaxies of their sample. The degree of systematic difference between PT and KCT in observed magnitudes (Fig. 4) is not uncommon when older photographic data is compared to modern photoelectric or CCD data (see Burstein *et al.* 1987 in their discussion of older photometry for southern hemisphere elliptical galaxies). If this is true, then the slope of the true blue Tully-Fisher relation for the galaxies in Figure 3 will be significantly steeper than that derived by KCT from their present data.

b) How Reliable are the Blue Magnitudes of the 13 Calibrator Galaxies?

Almost all of these galaxies have blue magnitudes that were derived from photographic surface photometry (see, e.g., sources listed in the RSA and the RC2). As illustrated by the specific case of N224, the blue magnitudes for these galaxies may very well be in error by over 0.2 mag when compared to CCD–derived magnitudes.

c) What are the Distances to the Calibrator Galaxies?

Differences of the order of 0.2–0.3 mag still exist, as evidenced by the comparison between PT and KCT. Obviously, if

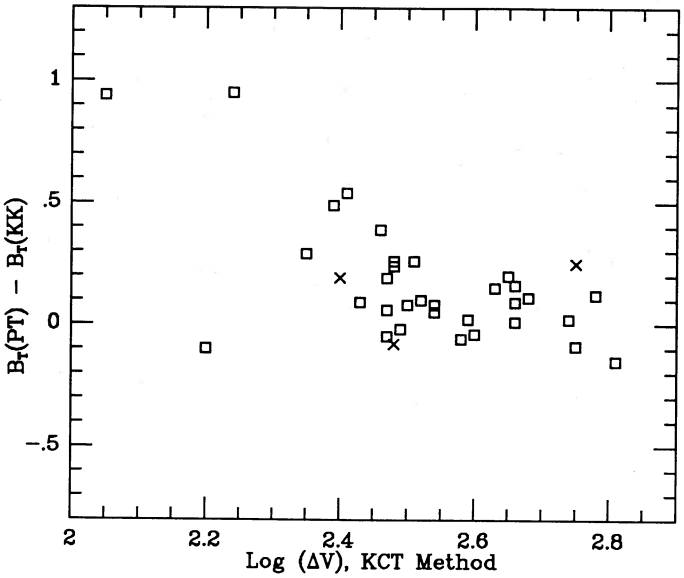

FIG. 4.—The difference between observed B_T magnitude (i.e., no corrections applied), in the sense PT − KCT, as a function of log ΔV_{20} as defined by KCT. Open squares represent the data for 32 Virgo cluster galaxies; crosses represent the data for the three calibrator galaxies N224, N598, and N2403. KCT-compatible data for the galaxies not listed by KCT are taken from the Kraan-Korteweg (1986) catalog.

no general agreement can be reached on these distances, no general agreement can be expected to emerge on distances of more distant galaxies from the application of the Tully-Fisher relation.

d) Which Galaxies Actually belong to the Virgo Cluster Proper?

The infall velocity field around a cluster makes it inherently difficult to identify which galaxies are actually in the cluster, and which are on its outskirts, falling in. PT acknowledge this fact explicitly and allow for it in their estimates of intrinsic scatter in the Tully-Fisher relation. Yet, judgment of which galaxies are true " Virgo " galaxies and which are outliers must remain somewhat subjective in the presence of noisy data and a pattern of velocity infall that is still in question (see Faber and Burstein 1989).

e) Is the Blue Tully-Fisher Relation Linear?

Aaronson *et al* (1986) have argued that the near-infrared Tully-Fisher relation is not linear and have fitted their data with a quadratic relationship. In its current form, the blue Tully-Fisher relation for Virgo cluster galaxies also appears to be curved, but in the sense *opposite* to that seen in the *H* passband by Aaronson *et al.*: luminosity increases with rotation velocity faster than a linear law in the *B* passband. The analysis of PT sidesteps this issue by directly comparing the distance modulus values for their three calibrator galaxies to the observed data for their Virgo cluster sample. The analysis of KCT assumes a linear relation and, with most of their galaxies being faint, derives a slope that predicts too faint a magnitude for the brightest galaxies.

Given all these considerations, how does one determine the best distance modulus to the Virgo cluster from blue magnitudes and the Tully-Fisher relation? It should be clear that one of the first priorities is the acquisition of new data to determine magnitudes of both Virgo galaxies and calibrator galaxies that are demonstrably on the same consistent system. Although this presents a very serious problem for the blue magnitude Tully-Fisher relation, it also afflicts, to lesser degrees, data taken at other wavelengths (see discussion of PT).

Magnitudes obtained in all the optical and near-infrared passbands currently in use for Tully-Fisher distance determinations are defined within given isophotal radii. Both magnitudes and radii are subject to inclination corrections due to dust obscuration, with the largest such corrections being for data taken in the blue passband. The lack of unanimity on the size of these corrections injects the greatest systematic uncertainty into distance estimates from the blue Tully-Fisher relation. The different methods of applying inclination corrections to observed rotation velocity widths lead to equally important systematic differences in the Tully-Fisher relation at any wavelength.

The present analysis has also raised a potentially troubling issue: does the distance modulus of Virgo determined from faint galaxies (i.e., those with log ΔV_{20} less than 2.4) differ systematically from that determined from brighter galaxies? The present blue magnitudes of KCT imply that this is the case, as shown in § III. The Virgo sample of PT cannot be used to answer this question, as it is restricted to brighter galaxies. Moreover, correcting the sense of systematic error in the values of B_T used by KCT would make their galaxies fainter, and thus assign them to greater distances.

The past 10 yr has shown an enormous increase in the number of galaxies to which we think we can reliably estimate distances. Over the same period of time the Tully-Fisher relation for spiral galaxies, one of the principal distance-measuring techniques, has consistently yielded a range of over 0.5 mag in estimates of the distance modulus of the Virgo cluster, perhaps the most studied cluster in the sky. In the use of the Tully-Fisher relationship by various groups there is no general agreement on: magnitudes of the Virgo cluster galaxies; inclination corrections to diameters, magnitudes and rotation velocities; choice of calibrator galaxies; and distances and magnitudes of these calibrator galaxies. In the absence of general agreement on these issues, there is little hope of unambiguously determining the distance to the Virgo cluster from this, or any other method that uses the integrated physical properties of spiral galaxies to estimate their distances.

This research is supported in part by an ASU Faculty Grant-in-Aid. S. R. is supported by the Isaac Newton Studentship at the University of Cambridge. We would both like to thank Donald Lynden-Bell for useful discussions, and D. B. is grateful to the astronomers and staff of the Institute of Astronomy for their hospitality while much of this research was done.

REFERENCES

Aaronson, M., Bothun, G., Mould, J. R., Huchra, J. P., Schommer, R. A., and Cornell, M. E. 1986, *Ap. J.*, **302**, 536.
Aaronson, M., *et al.* 1982, *Ap. J. Suppl.*, **50**, 241.
Ames, A. 1930, *Harvard Obs. Ann.*, **88**, Pt 1.
Binggeli, B., Sandage, A., and Tammann, G. A. 1985, *A.J.*, **90**, 1681.
Bottinelli, L., Gouguenheim, L., Paturel, G., and de Vaucouleurs, G. 1984, *Ap. J.*, **280**, 34.
Burstein, D., Davies, R. L., Dressler, A., Faber, S. M., Lynden-Bell, D., Terlevich, R. J., and Wegner, G. 1988, in *Large-Scale Structure and Motions in the Universe*, ed. G. Giuricin, F. Mardirossian, M. Mezzetti, and M. Ramella (Kluwer: Trieste), p. 179.
Burstein, D., Davies, R. L., Dressler, A., Faber, S. M., Stone, R. P. S., Lynden-Bell, D., Terlevich, R. J., and Wegner, G. 1987, *Ap. J. Suppl.*, **64**, 601.
Burstein, D., and Heiles, C. 1984, *Ap. J. Suppl.*, **54**, 33.
de Vaucouleurs, G., de Vaucouleurs, A., and Corwin, H. G. 1976, *Second Reference Catalog of Bright Galaxies* (Austin: University of Texas Press) (RC2).
de Vaucouleurs, G., and Pence, W. D. 1979, *Ap. J. Suppl.*, **40**, 425.
Faber, S. M., and Burstein, D. 1989, in *Proc. 27th Vatican Study Week, Large-Scale Motions in the Universe*, ed. V. C. Rubin and G. Coyne (Princeton: Princeton University Press), p. 115.
Fouque, P., Bottinelli, L., Gougueheim, L., and Paturel, G. 1989, *Ap. J.*, submitted.
Giovanelli, R., and Haynes, M. P. 1983, *A.J.*, **88**, 881.
Holmberg, E. 1958, *Medd. Lund Astr. Obs.*, Ser. II, No. 136.
Kraan-Korteweg, R. C. 1986, *Astr. Ap. Suppl.*, **66**, 255.
Kraan-Korteweg, R. C., Cameron, L. M., and Tammann, G. A. 1988, *Ap. J.*, **331**, 620 (KCT).
Pierce, M., and Tully, R. B. 1988, *Ap. J.*, **330**, 579 (PT).
Sandage, A., and Tammann, G. A. 1981, *A Revised Shapley-Ames Catalog of Bright Galaxies* (Washington DC: Carnegie Institution of Washington).
Tully, R. B., and Fisher, J. R. 1977, *Astr. Ap.*, **54**, 661.
Tully, R. B., and Fouque, P. 1985, *Ap. J. Suppl.*, **58**, 67.
Tully, R. B., and Shaya, E. J. 1984, *Ap. J.*, **281**, 31.
Zwicky, F., Herzog, E., and Wild, P. 1960–1963, *Catalogue of Galaxies and of Clusters of Galaxies*, Vols. **1** and **2** (Pasadena: California Institute of Technology).

DAVID BURSTEIN: Department of Physics, Arizona State University, Tempe, AZ 85287

SOMAK RAYCHAUDHURY: Institute of Astronomy, University of Cambridge, The Observatories, Madingley Road, Cambridge CB3 0HA, England, UK