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THE TULLY-FISHER RELATION AND H_0

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ABSTRACT

The use of the Tully-Fisher (TF) relation for the determination of H_0 relies on the availability of an adequate template TF relation and of reliable primary distances. Here we use a TF template relation with the best available kinematical zero point, obtained from a sample of 24 clusters of galaxies extending to $cz \sim 9000$ km s^{-1}, and the most recent set of Cepheid distances for galaxies fit for TF use. The combination of these two ingredients yields $H_0 = 69 \pm 5$ km s^{-1} Mpc^{-1}. The approach is significantly more accurate than the more common application with single cluster (e.g., Virgo, Coma) samples.

Subject headings: cosmology: distance scale — cosmology: large-scale structure of universe — cosmology: observations — galaxies: distances and redshifts — infrared: galaxies

1. INTRODUCTION

The Tully-Fisher (1977, hereafter TF) relation is a scaling law that correlates the luminosity and the rotational velocity of spiral galaxies, well suited to yield estimates of distance ratios between galaxies or galaxy aggregates. Once calibrated by means of a reliable *kinematical zero point*, the TF relation can be profitably used to measure peculiar velocities $V_{\rm pec}$, i.e., deviations from smooth Hubble flow. It can also be used in the measurement of the Hubble constant, H_0 (see Jacoby et al. 1992, and references therein); to that end, however, an additional calibration is needed for the absolute magnitude scale. The latter can be obtained from galaxies suitable for TF use with available primary distances. The number of such objects is rapidly growing because of the expansion of the Cepheid horizon made possible by the *HST*. Optimization of the kinematical calibration has received less attention, and we make it our main target in this letter.

Suppose fluxes and velocity widths are measured for a sample of galaxies in a cluster and that a set of nearby spiral galaxies have Cepheid distances. Matching the TF diagram of the cluster to that of the nearby calibrators yields a distance modulus for the cluster; then a measure of its systemic radial velocity can yield an estimate of H_0. The systemic radial velocity is, however,

$$cz = H_0\, d + [\boldsymbol{V}_{\rm pec}(\boldsymbol{d}) - \boldsymbol{V}_{\rm pec}(0)] \cdot (\boldsymbol{d}/d), \tag{1}$$

where $\boldsymbol{V}_{\rm pec}$ is the peculiar velocity vector, $\boldsymbol{d}$ is the vector distance to the galaxy, d is its modulus and $\boldsymbol{V}_{\rm pec}(0)$ can be inferred from the cosmic microwave background (CMB) dipole. Thus, solving for H_0 still requires knowledge of the peculiar velocity of the cluster. The Virgo cluster has often been a target of such application: it is nearby, it is well studied, and Cepheids have been discovered in several of its member galaxies. The uncertainty on its peculiar velocity is, however, still large (see Freedman et al. 1994a) and amounts to a sizable fraction of the cluster redshift, so that it percolates heavily in the derived H_0 error budget. A standard technique to circumvent this problem is that of bootstrapping the uncertainty to a more distant cluster, e.g., Coma (Freedman et al. 1994a; Tanvir et al. 1995; Yasuda & Okamura 1996). Using techniques such as TF that yield reliable distance ratios, the distance ratio between, say, Virgo and Coma can be obtained. Since Coma is nearly 6 times farther than Virgo, the ratio between the uncertain cluster peculiar velocity and its redshift is likely to be smaller. The TF kinematical calibration is implicitly obtained by assuming that the distant cluster is at rest in the comoving reference frame: the relative error thus introduced equals the ratio between the unknown peculiar velocity and the systemic velocity of the cluster.

The limitations of this approach are numerous. Cluster peculiar velocities can be large, and an important fraction of the redshift even for Coma. Estimates of the amplitude of cluster peculiar motions still differ: while the recent measurements of Giovanelli et al. (1997b) yield motions not exceeding 600 km s^{-1}, other sources report significantly larger values (Lauer & Postman 1994; see also Moscardini et al. 1996 and Bahcall & Oh 1996). Moreover, as the distance of the cluster increases, so does the amplitude of the incompleteness bias and that of its correction. Finally, a TF template relation extracted from a single cluster is naturally restricted to the

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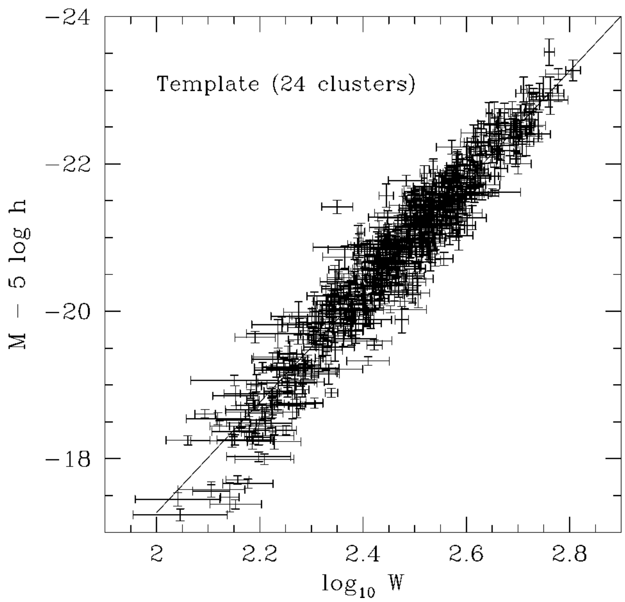

FIG. 1.—Template relation based on 555 galaxies in 24 clusters. The fit is -21.00 ± 0.02–7.68 ± 0.13 (log $W - 2.5$).

inclusion of, at most, a few dozen relatively bright galaxies, limiting the statistical accuracy in the definition of slope and offset of the TF template relation. The addition of faint objects can actually increase the scatter, as well as introduce nonlinearity in the TF diagram: their inclusion in a TF template is thus of negligible or perhaps even negative consequence (Giovanelli et al. 1997b).

Rather than using a single cluster in obtaining a TF template, the kinematical calibration of the TF relation is better achieved by using a "basket of clusters." The quality of the kinematical calibration thus obtained improves as the sky coverage of the cluster distribution becomes more isotropic and as the redshift distribution becomes deeper, even becoming impervious to the possible presence of large-scale bulk flows. Moreover, the global template that can be obtained from such a set is richer and has significantly better defined TF parameters (slope, offset) than those obtainable from any single cluster template. This approach resembles in some aspects that followed by Jerjen & Tammann (1993). In this Letter, we discuss such a TF template, survey the available literature on TF calibrators with Cepheid distances, and combine template and calibrators to derive an estimate of H_0.

2. A TF TEMPLATE RELATION

In a recent study (Giovanelli et al. 1997a, 1997b, hereafter G97a and G97b), 555 galaxies with TF measurements, located in the fields of 24 clusters, were used to produce a global TF template, for the estimate of peculiar velocities. The size of the cluster galaxy sample allows the application of strict membership criteria. The cluster distribution, which well approximates isotropy and extends to $cz \sim 9000$ km s^{-1}, makes possible a sensible definition of the kinematical zero point. Figure 1 shows the TF diagram from which the template relation is obtained, after a number of corrections were applied to the data, including those that take in consideration differences among morphological types, cluster sample incompleteness bias and cluster motions with respect to the CMB reference frame (see G97b). A few properties of the template are worth underscoring.

First, the dispersion about the TF mean relation is not well represented by a single figure of scatter. As shown in G97b, the scatter increases steeply as the velocity width diminishes. This has a strong effect in the computation of bias corrections and therefore on the vertical offset of the template. Second, the mean amplitude of the scatter is about 0.35 mag. Since the amplitude of the bias corrections scales with the scatter amplitude, the corrections we have estimated are smaller than those advocated by Sandage (1994), who finds a significantly larger mean scatter in the TF relation. Third, given the characteristics of the scatter, which are different from those assumed by Schechter (1980) and adopted by others, the idea that an inverse TF fit (i.e., one where log W is used as the "dependent" variable) is a bias-free tool is not well justified. The bias corrections applied to the data in Figure 1 were estimated within the framework of a bivariate TF fit, where magnitude was used as the dependent variable, and errors in both coordinates were taken into account. Figure 1 allows the prediction of $M_I - 5 \log h$ from a galaxy's velocity width; its combination with the measured flux then yields an estimate of the distance, scaled by h, which can be replaced in equation (1) to obtain the peculiar velocity. The kinematical calibration relies on how well the weighted mean of the peculiar velocities of the set of clusters approaches a null value. Note that even in the presence of a linear bulk flow, an isotropically distributed cluster set will yield a null mean velocity.

In addition to the statistical errors that arise from the TF scatter and the size of the sample, other sources of uncertainty affect the quality of the TF template, in the form of systematic errors. The first of those arises from the uncertainty in the cluster bias corrections, which depend on the assumed shape of the galaxy luminosity function. In G97b we estimate that contribution to the uncertainty of the template zero point to be about 0.03 mag. The second, and more important, term depends on how good the determination of the kinematical zero point is for the cluster sample. If in the cluster peculiar velocity distribution function motions in excess of $\sim$600 km s^{-1} are rare, as suggested by the results in G97b and illustrated in Bahcall & Oh (1996), the rms departure from null velocity expected for an isotropic cluster average will translate in a TF template zero-point uncertainty of about 0.04 mag, as discussed in G97b. If, on the other hand, a broader range of peculiar velocities is allowed (as shown, e.g., in Moscardini et al. 1996), its effect on the uncertainty of the TF zero point may be as large as 0.06 mag. The combination of statistical and systematic uncertainties on the TF offset can thus amount to as much as 0.05–0.07 mag. This is significantly lower than, for example, a 10% ($\sim$0.2 mag) uncertainty due to the unknown peculiar velocity of a single cluster.

3. TF GALAXIES WITH CEPHEID DISTANCES

The number of spiral galaxies with distance determination via the Cepheid period-luminosity relation has grown rapidly in the last couple of years (see papers in Livio, Donahue, & Panagia 1997) and as a result so has the number of "Cepheid calibrators" of the TF relation. The template discussed in § 2 refers to fluxes gathered in the I band. In Table 1, we include galaxies with measured I-band magnitudes, valid estimates of the velocity width and Cepheid distances known to us. The I-band magnitudes (col. [5]) are mostly those measured by Pierce & Tully (1992) and Pierce (1996), except for NGC 1365, for which we use the average magnitude between those

TABLE 1

TF CEPHEID CALIBRATORS: ADOPTED PARAMETERS

NGC (1)	M (2)	T (3)	i (4)	I_{tot} (5)	A_{gal} (6)	A_{int} (7)	β_{typ} (8)	DM (9)	References (10)	M_I (11)	log W (12)	References (13)
224	31	3	78	2.18	0.14	0.65	0.10	24.44 ± 0.12	18	−23.15 ± 0.21	2.663 ± 0.039	22, 2, 6, 8, 25
300		8	43	7.36	0.02	0.09	0.00	26.66 ± 0.15	18	−19.42 ± 0.18	2.269 ± 0.033	20
598	33	5	57	4.98	0.07	0.20	0.00	24.63 ± 0.10	18	−19.92 ± 0.17	2.286 ± 0.032	7, 8, 21, 23
925		5	57	9.30	0.11	0.26	0.00	29.84 ± 0.16	31	−20.92 ± 0.18	2.330 ± 0.046	8, 9, 10, 15, 24, 34
1365		3	48	8.35	0.00	0.11	0.10	31.30 ± 0.17	32	−23.16 ± 0.19	2.684 ± 0.015	3
2366		8	69	11.05	0.07	0.22	0.00	27.68 ± 0.20	19	−16.92 ± 0.22	1.887 ± 0.077	9, 34
2403		5	59	7.39	0.06	0.25	0.00	27.51 ± 0.15	18	−20.43 ± 0.18	2.389 ± 0.042	4, 10, 24, 29, 34
3031	81	2	57	5.70	0.08	0.28	0.32	27.80 ± 0.20	12	−22.78 ± 0.18	2.602 ± 0.055	1, 9, 13, 24
3109		10	80	9.23	0.06	0.35	0.00	25.50 ± 0.20	5	−16.68 ± 0.22	2.079 ± 0.043	8, 10, 16
3368	96	2	42	8.10	0.03	0.15	0.32	30.32 ± 0.16	33	−22.72 ± 0.19	2.633 ± 0.034	14
4321	100	5	28	8.22	0.02	0.06	0.00	31.16 ± 0.15	11	−23.02 ± 0.16	2.681 ± 0.063	14
4496		5	34	10.88	0.00	0.08	0.00	31.13 ± 0.13	27	−20.33 ± 0.16	2.412 ± 0.080	10
4536		4	70	9.53	0.01	0.45	0.00	31.10 ± 0.13	26	−22.04 ± 0.18	2.489 ± 0.016	9, 15
4639		3	55	10.49	0.02	0.24	0.10	32.00 ± 0.23	28	−21.87 ± 0.25	2.502 ± 0.025	10
5457	101	5	21	6.97	0.00	0.04	0.00	29.34 ± 0.17	17	−22.41 ± 0.15	2.560 ± 0.077	9, 10, 30

NOTE.—M31, M33: warped disk; perturbed velocity field. N2366, N3109: low-luminosity objects; poor rotation widths; inadequate for TF use. M81: main member in strongly interacting system; disturbed, highly asymmetrical velocity field. N4496: galaxy superimposed in projection; poor photometry; inadequate for TF use.

References.— (1) Appleton et al. 1981; (2) Brinks & Burton 1984; (3) Bureau et al. 1996; (4) Burns & Roberts 1971; (5) Capaccioli et al. 1992; (6) Cram et al. 1980; (7) Corbelli et al. 1989; (8) Dean & Davies 1975; (9) Dickel & Rood 1978; (10) Fisher & Tully 1981; (11) Freedman et al. 1994a; (12) Freedman et al. 1994b; (13) Gottesman & Weliachew 1975; (14) Haynes & Giovanelli 1996; (15) Hewitt et al. 1982; (16) Jobin & Carignan 1990; (17) Kelson et al. 1996; (18) Madore & Freedman 1991; (19) Pierce & Tully 1992; (20) Puche et al. 1990; (21) Reakes & Newton 1978; (22) Roberts & Whitehurst 1975; (23) Rogstad et al. 1976; (24) Rots 1980; (25) Rubin & Ford 1970; (26) Saha et al. 1996; (27) Sandage et al. 1997; (28) Sandage et al. 1997; (29) Shostak 1978; (30) Shostak & Allen 1980; (31) Silbermann et al. 1996; (32) Silbermann et al. 1997; (33) Tanvir et al. 1995; (34) Wevers et al. 1986.

published by Mathewson et al. (1992) and by Bureau, Mould, & Staveley-Smith (1996). Velocity widths (col. [12]) have been garnered from sources in the public domain, as indicated in column (3). The corrections applied to the observed values, to account for disk inclination, turbulence contributions, etc., are those described in G97a. The morphological type correction β_{typ}, listed in column (8), is a term to be subtracted from the magnitude, that takes into consideration mean offsets of galaxies of different types from those of type Sbc/Sc, as discussed in G97b. The adopted distance moduli are listed in column (9). Galactic and internal extinctions (cols. [6] and [7]) are estimated using the procedures described in G97a. NGC and Messier numbers are given in columns (1) and (2), while RC3 type and inclination are listed in columns (3) and (4).

Many of the objects listed in Table 1 are not ideal for TF use. M100, M101, and N4496 are uncomfortably close to face-on, requiring large inclination corrections to the widths. M31, M33, and M81 exhibit severe perturbations in the velocity field. NGC 2366 and NGC 3109 are dwarf irregular systems, very ill-suited for use with a template that is principally constructed using luminous spirals; for dwarf systems, moreover, it is difficult to estimate accurately the actual contribution to the width of rotational motions, and their scatter about the TF relation is huge (Hoffman & Salpeter 1997). Figure 1 exhibits a hint of nonlinearity in the TF template relation, in the sense that low width galaxies may be fainter, on the average, than indicated by the straight line fit to the data. This effect is difficult to quantify, as the TF scatter rises steeply with decreasing width. The combined effect of these uncertainties suggests that it would be best dropping NGC 2366 and NGC 3109 from the sample. NGC 4496 is not only nearly face-on, but a second galaxy is seen superimposed on its disk, making the extraction of photometric parameters from its image highly uncertain. We note one further caution. Our estimates of TF parameters in Table 1 are based on a somewhat subjective synthesis of a large amount of heterogeneous material, especially concerning the velocity widths, sometimes involving the measurement of spectra on paper copies of published data figures. Our assignment of error bars to the data is thus reflective of this unorthodox method of parameter derivation, rather than of the original accuracy of the data, and it is likely to underestimate somewhat the amplitude of the uncertainty.

4. THE VALUE OF H_0

In Figure 2, the data of all galaxies listed in Table 1 are plotted over a grid of renditions of the TF template, each for

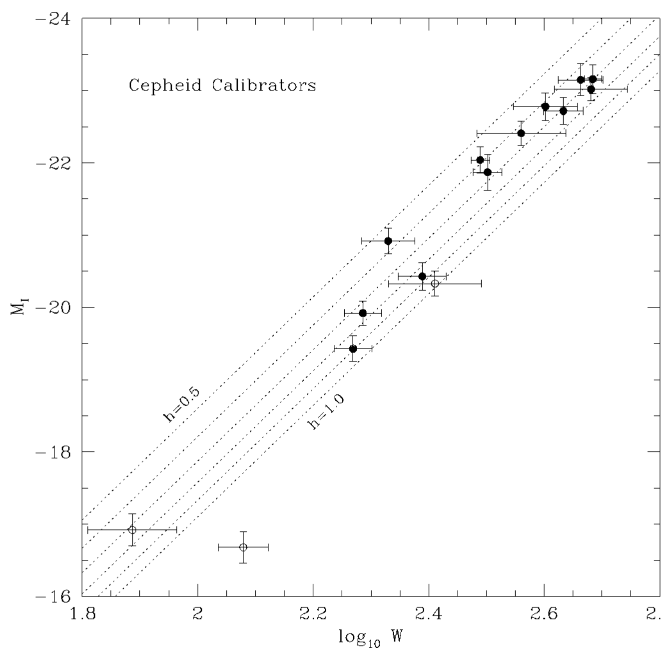

FIG. 2.—TF calibrators with Cepheid distances, superimposed on a grid of TF template relations plotted for different values of h. The unfilled symbols represent galaxies unfit for TF work, as explained in the text.

a different value of h between 0.5 and 1.0. The three objects ill-suited for TF use (NGC 4496, NGC 2366 and NGC 3109), as discussed in § 3, are plotted by unfilled symbols in Figure 2. Excluding them as calibrators, we restrict the set to the 12 remaining galaxies. Keeping the slope of the TF template fixed, we compute the value of h that yields χ^2 minimization of residuals for the set of calibrators, which is $h = 0.69 \pm 0.02$. The formal error of $\sim$0.06 mag does not account for the systematic uncertainty on the TF relation zero point discussed in § 2, nor possible systematic uncertainties on the period-luminosity relation of Cepheid distances, arbitrarily taken as 0.1 mag. When systematic uncertainties are included,

$$H_0 = 69 \pm 5 \text{ km s}^{-1} \text{ Mpc}^{-1}. \qquad (2)$$

This result is more robust than those derived purely from distances to galaxies in Virgo, or M96, or from applications that rely on bootstraps of the distances of those aggregates to that of Coma.

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