

Read the paper "The Extragalactic Distance Scale Without Cepheids" by Mould and Sakai.

1. (40 points) Measuring distances in astronomy. For each of following techniques, discuss:
 - i) qualitative description of how technique works, including as many details as you can
 - ii) quantitative formula showing how technique is used to derive distance
 - iii) distance range over which technique can be applied
 - iv) estimate of precision and accuracy (where relevant, note the distinction!) of technique and what limits them
 - (a) parallax
 - (b) cluster main sequence fitting
 - (c) spectroscopic parallax
 - (d) tip of the red giant branch
 - (e) Tully-Fisher relation
 - (f) surface brightness fluctuations
 - (g) type Ia supernovae
 - (h) Hubble law
2. (20 points) Observational issues
 - (a) What is an aperture correction, as mentioned in Section 2, paragraph 4?
 - (b) What are charge transfer effects (CTE), as mentioned in Section 2, paragraph 4?
 - (c) What is an isophotal magnitude (section 3, paragraph 1)?
 - (d) What is a 20% velocity width (section 3, paragraph 1)?
 - (e) What is the inclination correction mentioned in section 3, paragraph 1?
3. (20 points) Cepheids and stellar evolution
 - (a) (5 points) What is a Cepheid variable, and how are they used to measure distances?
 - (b) (10 points) What is the "instability strip"? What are some of the different types of variable stars that are found in the instability strip? Sketch a HR diagram, quantitatively label the axes, and show the location of the instability strip.
 - (c) (5 points) What is meant by the statement in the first paragraph of the paper: "the finite width of the Cepheid instability strip in the HR diagram implies that nuisance parameters such as metallicity and star formation history may play a role in determining the PL relation?"
4. (20 points) Cosmology

OVER

- (a) (5) What is the observational definition of the Hubble constant?
- (b) (5) What are the units of the Hubble constant, and what is the currently accepted value? What does the value $1/H_0$ relate to?
- (c) (5) What is the theoretical definition of the Hubble constant, i.e. what is its formulation in terms of cosmological parameters? Is it expected to vary with time, and if so, how?
- (d) (5) What are the cosmological parameters currently thought to be important for characterizing the expansion of the Universe? What are currently accepted values/ranges for these parameters?

THE EXTRAGALACTIC DISTANCE SCALE WITHOUT CEPHEIDS

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ABSTRACT

Distances of galaxies in the *Hubble Space Telescope* Key Project are based on the Cepheid period-luminosity relation. An alternative basis is the tip of the red giant branch. Using archival *HST* data, we calibrate the infrared Tully-Fisher relation using 14 galaxies with tip of the red giant branch measurements. Compared with the Key Project, a higher value of the Hubble constant by $10\% \pm 7\%$ is inferred. Within the errors the two distance scales are therefore consistent. We describe the additional data required for a conclusive tip of the red giant branch measurement of H_0 .

Subject headings: distance scale — galaxies: distances and redshifts

1. INTRODUCTION

The extragalactic distance scale based on the Cepheid period-luminosity (PL) relation and secondary distance indicators, such as the Tully-Fisher relation, the supernova standard candle (Gibson et al. 2000), surface brightness fluctuations, and the fundamental plane (Freedman et al. 2001; Mould et al. 2000), has been criticized recently (Tammann et al. 2008a; Sandage & Tammann 2006) on the grounds that the PL relation may not be unique. Indeed, the finite width of the Cepheid instability strip in the HR diagram implies that nuisance parameters such as metallicity and star formation history may play a role in determining the PL relation. Metallicity was considered as a second parameter by Freedman et al. (2001), Sakai et al. (2004), and Macri et al. (2006). Romaniello et al. (2008) have reviewed the situation and concluded that the Cepheid PL relation is not universal.

It is of interest, therefore, to see how well the distance scale can be measured without reference to Cepheids at all. In this Letter we use the tip of the red giant branch (TRGB) distance indicator to calibrate the Tully-Fisher relation. The TRGB is a good standard candle because it results from the helium flash on the red giant branch, which theory suggests is relatively immune to metallicity effects in old stellar populations.

2. TRGB DISTANCES

The TRGB is unquestionably the most practical distance indicator for nearby galaxies. It is versatile, fast, and theoretically verified (Salaris & Cassisi 1997; Madore & Freedman 1999; Salaris et al. 2002).

The zero point of the TRGB magnitude, however, has been debated in several papers. Da Costa & Armandroff (1990) first derived the bolometric magnitude of the TRGB. The distance modulus measured by the TRGB method is then estimated via $(m - M)_I = I_{\text{TRGB}} - M_{\text{bol}} + \text{BC}_I$, where the bolometric correction (BC_I) and the bolometric magnitude (M_{bol}) are both dependent on the color of the TRGB stars. Using this calibration, the TRGB magnitude in I band is determined to be between -3.95 and -4.1 depending on the colors of the RGB stars found. The absolute zero point of this calibration was based on the distances to Galactic globular clusters that were measured using the RR Lyrae method zero point based on Lee et

al. (1990). On the other hand, Salaris & Cassisi (1997) presented a theoretical calibration of the TRGB zero point and concluded that the empirical calibration by Da Costa & Armandroff was too faint by ~ 0.1 mag, likely due to the fact that the RGB population of Galactic globular clusters used in the empirical calibration were not well populated around the tip.

Most recently, Rizzi et al. (2007) explored the calibration issue and established a new calibration based on the assumed luminosity for the horizontal branch and the identification of this feature in five Local Group galaxies. This calibration gives the I -band TRGB magnitude of -4.05 at $(V - I) = 1.6$ mag. Furthermore, the Rizzi et al. (2007) calibration is not linked to the Cepheid distance scale in any way and is completely independent.

The sample for this section was drawn from those galaxies within 10 Mpc with infrared photometry, distance estimates, and 21 cm data cataloged by Aaronson et al. (1982) and with V and I imaging in the *Hubble Space Telescope* data archive (Table 1). These images were downloaded and photometry carried out with the DAOPHOT software of Stetson (1987). Point-spread functions (PSFs) supplied by Stetson for the H_0 Key Project were employed (Kennicutt et al. 1995) for WFPC2 data. For ACS data we used PSFs constructed from the images themselves. The ALLSTAR program was run twice to obtain as deep a star list as possible. Areas of the galaxy with strong Population I signatures were edited out. Aperture corrections were made and color magnitude diagrams (CMDs) were calibrated and corrected for charge transfer effects (CTE) following Dolphin (2000).¹ ACS data were calibrated as described by Sirianni et al. (2005) and corrected for CTE using the standard algorithm.² CMDs for NGC 247, 891, 4826, 4945, and 5253 are shown in Figures 1–5.

For the detection of the TRGB in our target galaxies, we used the edge-detection method described in Sakai et al. (1996) and the results are recorded in Table 2. Reddening values in the table are those of Schlegel et al. (1998). Literature values of TRGB distance moduli are from Karachentsev et al. (2003) and Karachentsev (2005). We have preferred our value of TRGB, $I = 24.10$, to that of Davidge (2006) whose measure-

¹ See http://purcell.as.arizona.edu/wfpc2_calib.

² See http://www.stsci.edu/hst/acs/performance/cte/cte_formula_acs_page.pdf.

TABLE 1
HST DATA SETS

Galaxy	Archive Data Set	Filter
NGC 247	j9ra78kq, ksq, kuq, kwq	F606W, F814W
NGC 891	j8eo01e9q, edq, ehq, eyq, f3q, f7q, g0q, j8eo02ofq, owq, plq, p5q, q0q, q5q, q9q	F606W F814W
NGC 4826	j9ov16uaq, ubq, udq, ufq	F606W, F814W
NGC 4945	u6ep1101r, 1102r, 1103r, ..., 1109r, 110ar, 110br, 110cr	F606W, F814W
NGC 5253	j9k501dbq, deq, dmq, doq	F555W, F814W

ment of $i' = 24.5 \pm 0.1$ can be transformed to $I = 24.03$, using $V - I = 1.6$ and the formulae of Smith et al. (2002). Six galaxies in our sample have Cepheid distance moduli, and these are given in the last columns of Table 2.

3. MAGNITUDES AND VELOCITY WIDTHS

The principal sources of infrared and 21 cm data are Aaronson et al. (1982) and Sakai et al. (2000). For other galaxies we used isophotal magnitudes from the 2MASS Large Galaxy Atlas, transforming them with $H_{0.5}^c - H_{mk20fe} = 0.27 \pm 0.03$ mag, based on 123 galaxies in common. For NGC 4945 and 5102 we used 20% velocity widths from HIPASS (Meyer et al. 2004) and Tully (1988) respectively, correcting them for cosmology $(1+z)$ and inclination. Following Sakai et al. (2000) we omitted the 3° additive term in the inclination adopted by Aaronson et al. (1982) and Tully (1988). The fifth column of Table 2 is the corrected infrared magnitude; the sixth is the corrected velocity width.

4. CALIBRATION OF THE TULLY-FISHER RELATION

The Tully-Fisher relation for galaxies with TRGB distances is shown in Figure 6. The ordinate is the absolute H magnitude corrected for internal extinction following Sakai et al. (2000). To correspond in range of velocity width to that of the cluster galaxies to which the calibration will be applied (Aaronson et al. 1986), we ignore galaxies with $\Delta V(0) < 200$ km s $^{-1}$. The straight line in Figure 6 is the calibration by Sakai et al. (2000) using Cepheid distances. The mean difference in distance modulus between the 14 TRGB galaxies and the 21 Cepheid gal-

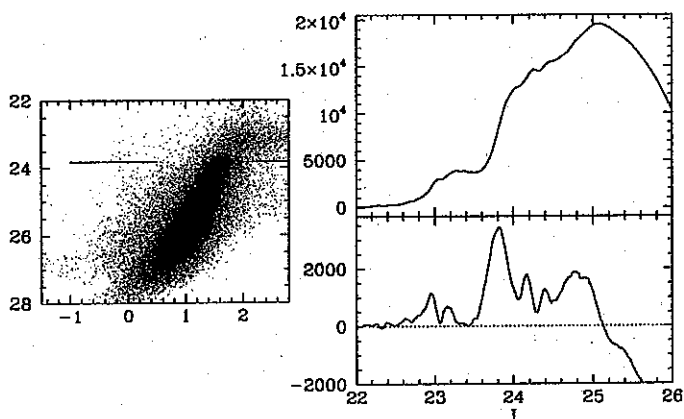


FIG. 1.—Left: Color-magnitude diagram of NGC 5253 with the TRGB marked. Top right: RGB luminosity function of NGC 5253. Bottom right: Peak in the filtered indicator of the TRGB, $I = 23.82$ mag.

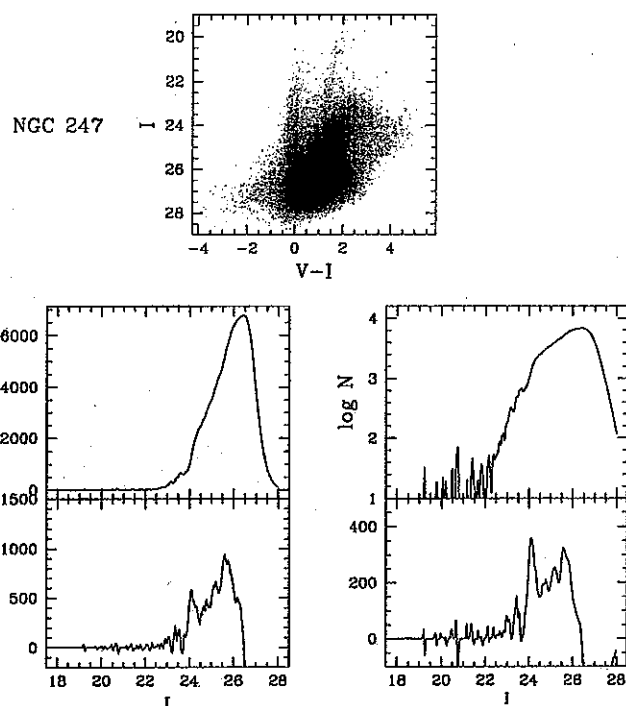


FIG. 2.—Top: CMD of NGC 247. Left, upper panel: RGB luminosity function. Right, upper panel: log luminosity function. Lower panels: Peak in the filtered indicator of the TRGB, $I = 24.10$ mag.

axies is 0.19 ± 0.13 mag. Applying their Cepheid Tully-Fisher calibration, Sakai et al. (2000) found $H_0 = 67 \pm 3 \pm 10$ km s $^{-1}$ Mpc $^{-1}$. With our TRGB Tully-Fisher relation applied to the same cluster data, we would obtain a 10% higher value, 73 ± 5 km s $^{-1}$ Mpc $^{-1}$, where our quoted uncertainty is the statistical error only.

5. DISCUSSION AND CONCLUSIONS

Sakai et al. (2000) obtained $H_0 = 71 \pm 4 \pm 7$ km s $^{-1}$ Mpc $^{-1}$ from their multiwavelength Cepheid-based Tully-Fisher

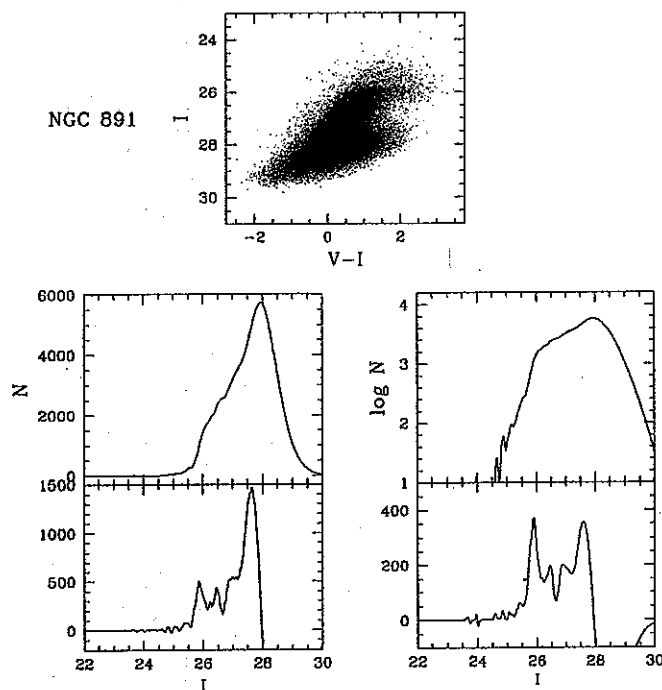


FIG. 3.—Top: CMD of NGC 891. The other panels follow Fig. 2 with $I = 25.90$.

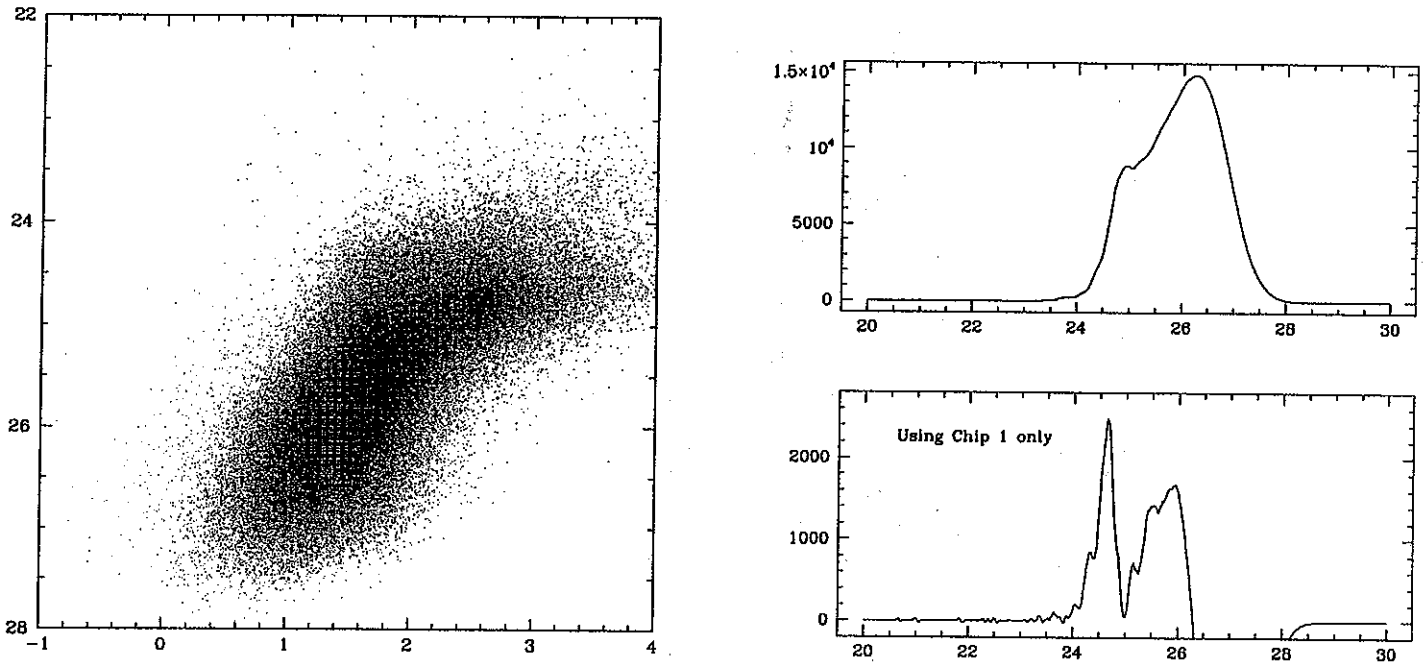


FIG. 4.—Left: CMD of NGC 4826. Top right: Luminosity function. Bottom right: Peak in the filtered indicator of the TRGB, $I = 24.64$.

calibration. The largest term in the $7 \text{ km s}^{-1} \text{ Mpc}^{-1}$ systematic error is due to the distance of the Large Magellanic Cloud. The largest term in the absolute calibration of the TRGB (Population II) distance scale is the uncertainty in $M_{I,\text{TRGB}} = -4.05 \pm 0.02 \text{ mag}$ (Rizzi et al. 2007), associated with the absolute magnitude of the horizontal branch.

Our principal finding is that, within the 1.5σ uncertainty, the mean difference of the distance moduli derived from Cepheids and from the TRGB magnitude for our sample of 14 galaxies is consistent with zero.

In addition, we conclude that the further steps to a more accurate Cepheid-independent value of H_0 are (1) a larger sample of TRGB distances to galaxies which calibrate secondary distance indicators, (2) multiwavelength photometry of these

galaxies, and (3) TRGB calibration of Type Ia supernovae (Tammann et al. 2008b), surface brightness fluctuations, and the fundamental plane.

This work is based on archival observations made with the *Hubble Space Telescope*, which is operated by the Space Telescope Science Institute under a contract with NASA. This work makes use of 2MASS data products, a joint project of the University of Massachusetts and IPAC/Caltech, funded by NASA and NSF. In addition to DAOPHOT, this research has made use of IRAF, which is distributed by NOAO. NOAO is operated by AURA under a cooperative agreement with NSF.

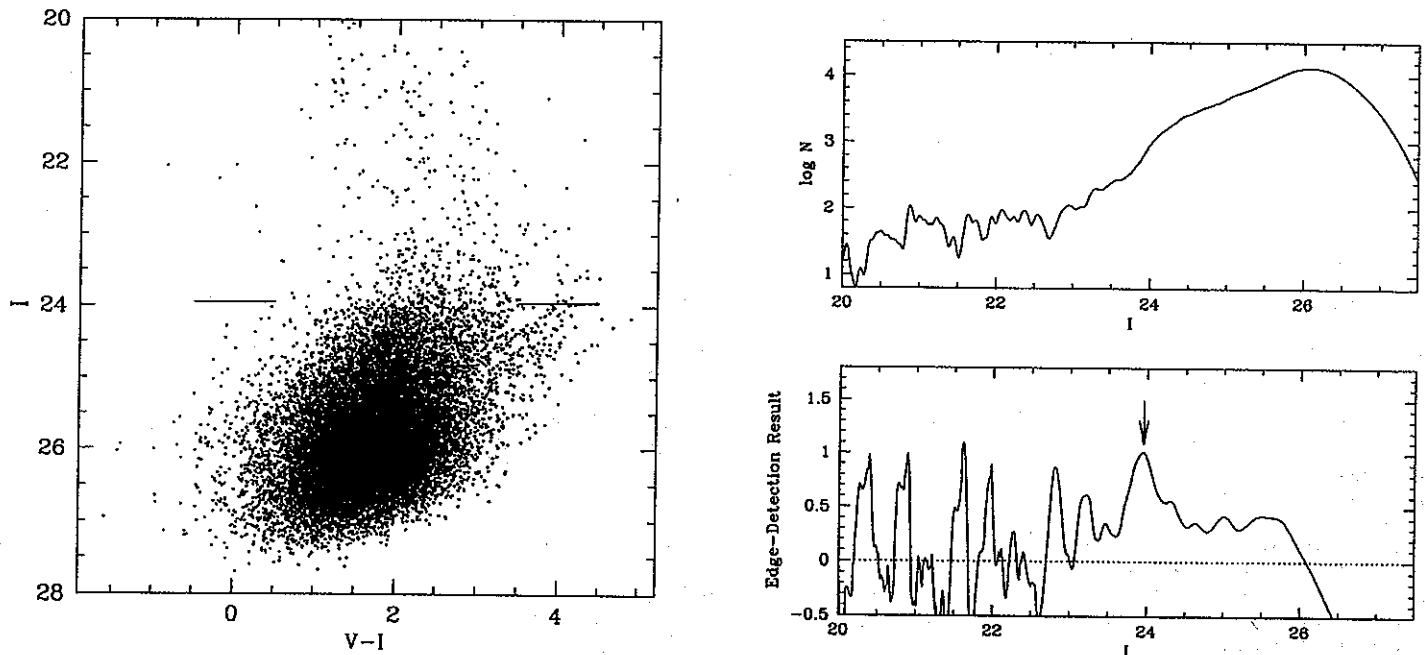


FIG. 5.—Left: CMD of NGC 4945. The other panels follow Fig. 4 with $I = 23.95$.

TABLE 2
GALAXIES CALIBRATING THE TULLY-FISHER RELATION

Galaxy	I_{TRGB}	A_I	$(m - M)_0$	$H_{-0.5}^c$	$\Delta V_{20}(0)$	Ref.	Cepheid Modulus	Ref.
NGC 7793	23.95	0.22	27.78	7.89	255	5		
NGC 224	20.53	0.15	24.37	0.91	555	1	24.44	8
NGC 247	24.10	0.03	28.12	7.69	233	2	27.80	9
NGC 253	23.97	0.19	27.83	4.74	443	5		
NGC 598	20.91	0.08	24.71	4.38	249	1	24.64	8
NGC 891	25.90	0.13	29.82	6.84	483	2		
NGC 3031	23.91	0.16	27.70	4.38	524	1	27.80	8
NGC 3351	25.92	0.05	29.92	7.45	385	1, 6	30.01	8
NGC 3621	25.38	0.16	29.26	7.40	316	1	29.13	8
NGC 4244	...	...	28.26	8.75	221	3		
NGC 4826	24.64	0.08	28.61	6.10	376	2		
NGC 4945	23.95	0.10	27.90	5.16	382	2, 4		
NGC 5102	...	...	27.66	7.57	235	3, 4		
NGC 5253	23.82	0.11	27.76	8.96	103	2	27.61	8
IC 5052	24.84	0.10	28.80	10.24	211	7		

REFERENCES.—(1) Rizzi et al. 2007; (2) this paper; (3) Karachentsev 2005; (4) <http://irsa.ipac.caltech.edu/applications/2MASS/LGA/>; (5) Karachentsev et al. 2003; (6) Sakai et al. 2000; (7) Seth et al. 2005; (8) Ferrarese et al. 2000; (9) Garcia-Varela et al. 2008.

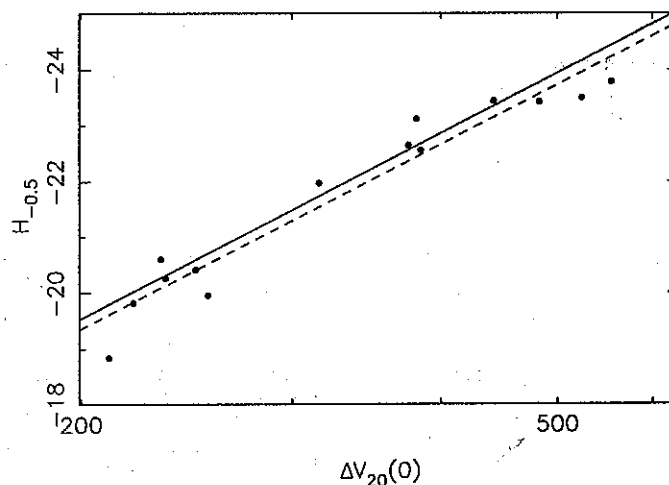


FIG. 6.—Tully-Fisher (TF) relation from the data in Table 2. The straight line is eq. (10) of Sakai et al. (2000) and represents the Cepheid infrared TF calibration. The dashed line is the least-squares regression to the data points.

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