THE ASTROPHYSICAL JOURNAL, 449:413–421, 1995 August 20

LIMITS ON THE HUBBLE CONSTANT FROM THE *HST* DISTANCE OF M100[1]

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Received 1994 December 15; accepted 1995 March 1

ABSTRACT

Because M100 is in the Virgo cluster, our recent measurement of its distance has an impact on the calibration of all of the extragalactic secondary distance indicators which reach beyond Virgo and define the expansion rate. We examine the consequences of a 17 Mpc M100 distance, questioning its consistency with supernova and other distances.

The distance of M100 provides two separate constraints on the Hubble constant. First, it verifies the emissivity calculations for Type II supernovae. These models, fitted to SN 1987A, have recently been used to measure host galaxy distances beyond 10^4 km s^{-1} recession velocity. Second, it constrains the distance of the Virgo cluster, which in spite of its apparent complex structure, provides an effective calibration for a set of reliable and well-used secondary distance indicators.

Reviewing the Type II supernova distances for three galaxies with Cepheid distances, we find consistency, which supports the recent SN result $H_0 = 73 \pm 11$ km s^{-1} Mpc^{-1}. This support is independent of where M100 lies in the Virgo cluster. Reviewing the Hubble recession velocity (cosmological redshift) of the Virgo cluster, we find $H_0 = 81 \pm 11$ km s^{-1} Mpc^{-1}, plus an additional uncertainty arising from the extended nature of the Virgo cluster.

Employing the Virgo cluster as calibrator, we obtain measurements of the Hubble constant from extant surface brightness fluctuation measurements, elliptical galaxy velocity dispersion measurements, the Tully-Fisher relation, and the Type Ia supernova standard candle. These yield $H_0 = 84 \pm 16$, 76 ± 10, 82 ± 11, and 71 ± 10 km s^{-1} Mpc^{-1}, respectively. All of these are consistent, but they are all subject to the additional uncertainty from Virgo's line-of-sight depth.

We explore a number of simple models of the structure of the Virgo cluster; these support the recent conclusion of Freedman and coworkers that the appropriate uncertainty to attach to the Hubble constant from the Cepheid distance to Virgo is 20%. A value of $H_0 = 80 \pm 17$ km s^{-1} Mpc^{-1} is consistent with all the data discussed herein. Confidence limits with 95% significance can be assigned to the interval $50 < H_0 < 100$ km s^{-1} Mpc^{-1}.

Further work in this program should be expected to identify the systematic differences between the distance indicators investigated here and constrain the Hubble constant to 10% accuracy.

Subject headings: distance scale — galaxies: clusters: individual (Virgo) — galaxies: distances and redshifts — galaxies: individual (M100) — supernovae: general

1. INTRODUCTION

Measurement of the distance of M100 from the period luminosity (PL) relation for Cepheid variables (Freedman et al. 1994a) is a major milestone in the quest for an accurate value of H_0. The *Hubble Space Telescope* key project to determine the extragalactic distance scale aims to measure H_0 to 10%. To achieve this goal will require Cepheid distance measurements for some 20 galaxies within a redshift of approximately 10^3 km s^{-1}. These galaxies in turn will calibrate five secondary distance indicators which will extend the volume over which the expansion rate has been measured to some 10^6 Mpc^3.

The purpose of this paper is to assess the impact of the distance of M100 on the extragalactic distance scale. In its way the Virgo cluster is as significant a junction in the distance

[1] Based on observations with the NASA/ESA *Hubble Space Telescope*, obtained through the Space Telescope Science Institute, which is operated by AURA, Inc., under NASA contract NAS 5-26555.

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scale as the Magellanic Clouds, permitting a consistency check on many secondary distance indicators. We are particularly interested in whether supernova distances are consistent with global indicators of galaxy distances based on their stellar populations. We examine whether *HST* Cepheid distances are tending to converge or maintain a bimodal extragalactic distance scale. We begin the process of seeking out systematic differences between secondary distance indicators. Our objective is not to present an ab initio recalibration of the distance scale but rather to use the M100 distance to constrain the global value of H_0, and assess the remaining degree of uncertainty in its value.

We find that the measurement of M100's distance aids in the calibration of a number of these secondary distance indicators. Freedman et al. (1994a) considered the redshift of Virgo and the distance of Coma in order to estimate H_0. The additional secondary distance indicators considered here support the conclusions of that work. The net result is a very significant constraint on the Hubble constant.

2. THE MEAN DISTANCE OF THE VIRGO CLUSTER

Like many clusters of galaxies, Virgo has a complex structure, which has been elucidated gradually, starting with the observations of de Vaucouleurs (1961) of distinct elliptical and spiral concentrations. M100 is a bona fide member of the Virgo cluster, well within the cluster confines in velocity space, as shown in Figure 1. The concentration on the sky of galaxies in this cluster is clearly delineated in Figures 2 and 3. M100 lies within the classical 6° circle of de Vaucouleurs (1961), and just outside the last X-ray contour in the *ROSAT* map of Böhringer et al. (1994).

Marked substructure exists in the Virgo cluster (Huchra 1985; Bingelli, Sandage, & Tammann 1985) with member galaxies exhibiting a spread in surface brightness fluctuation distances from 11 to 19 Mpc (Tonry, Ajhar, & Luppino 1990). We must therefore consider whether M100 is associated with the central concentration or the fringes of the cluster. Our goal is to place confidence limits on the distance of the Virgo cluster.

There are four relevant and quantitative constraints:

1. We have the result of Freedman et al. (1994a) that the distance of M100 is 17.1 ± 1.8 Mpc.

2. The Tully-Fisher (TF) relation for the Virgo cluster is a second constraint. Pierce & Tully (1988) find that M100 is 2.8 ± 2.3 Mpc more distant than the mean of the spiral galaxies in their optical and infrared photometric study of the Virgo TF relation. However, the inclination of the disk of M100 to the line of sight is only 27 ± 3 degrees, as estimated kinematically (Warmels 1988), and this low value detracts further from the formal significance of M100's residual in the TF relation.

3. Fouqué et al. (1990) provide the most comprehensive study of the TF relation in Virgo. The galaxies within 2° of M100 have a mean residual 0.13 ± 0.24 mag brighter than the TF relation for spiral galaxies within 2° of the elliptical galaxy M87.

4. We note that Pierce et al. (1994) have recently published a distance to the galaxy NGC 4571 from three Cepheid variables identified with CFHT. They find 14.9 ± 1.2 Mpc.

More subjective criteria offer little insight into the location of these galaxies relative to the cluster mean. Sandage & Bedke (1985) classify the resolvability of NGC 4571 as "excellent," but M100 as "fair." These are the two extrema of their scale,

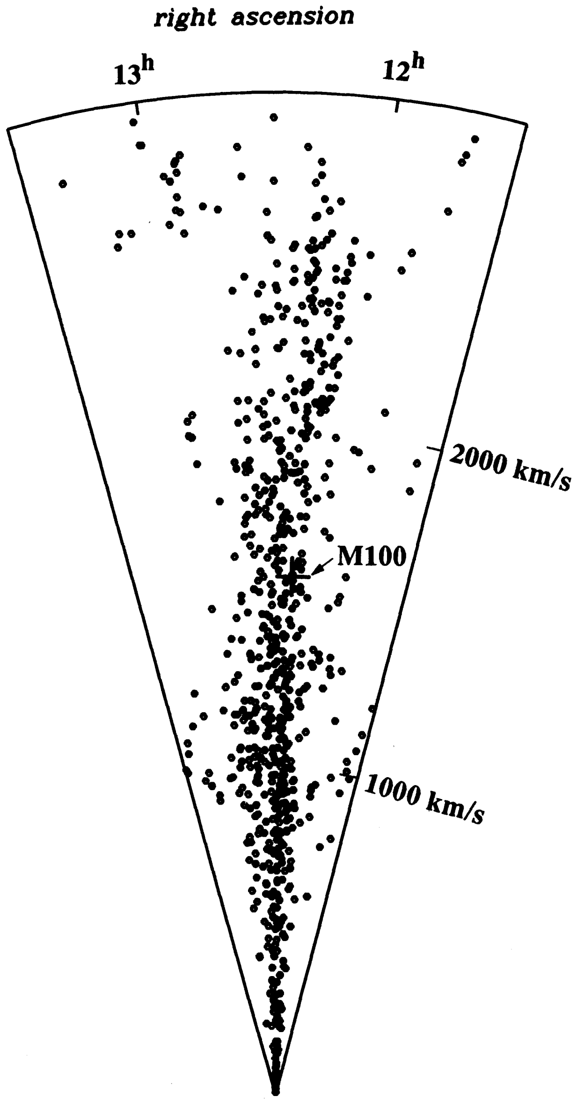

FIG. 1.—Location of M100 in a cone diagram of the Virgo cluster. Galaxies from $cz = 0$ to 3000 km s^{-1} and between $\delta = 0°$ and 24° are shown.

but the galaxies do not differ significantly in their independently determined Cepheid distances.

These constraints are consistent with the conclusion that M100 is a member of the Virgo cluster, whose centroid is at 17 Mpc. We examine the uncertainty in that distance with some parameterized models of the cluster in § 9.

3. THE COSMOLOGICAL REDSHIFT OF THE VIRGO CLUSTER

The simplest estimate of H_0 can be derived from the Virgo distance estimate of § 2 and the cosmological redshift of Virgo. The cosmological velocity is estimated by determining the cluster's heliocentric velocity, correcting that to the centroid of the Local Group, and determining the peculiar velocity of the Local Group with respect to the Hubble flow.

Modern determinations of the cluster velocity are based on Huchra's (1985) catalog of Virgo galaxy velocities (Huchra 1985, 1988; Binggeli, Sandage, & Tammann 1987). Derived values of the heliocentric cluster velocity range from 1079 ± 48 km s^{-1} to 1151 ± 38 km s^{-1} and depend on the precise coordinates used for the cluster center, the inclusion or exclusion of

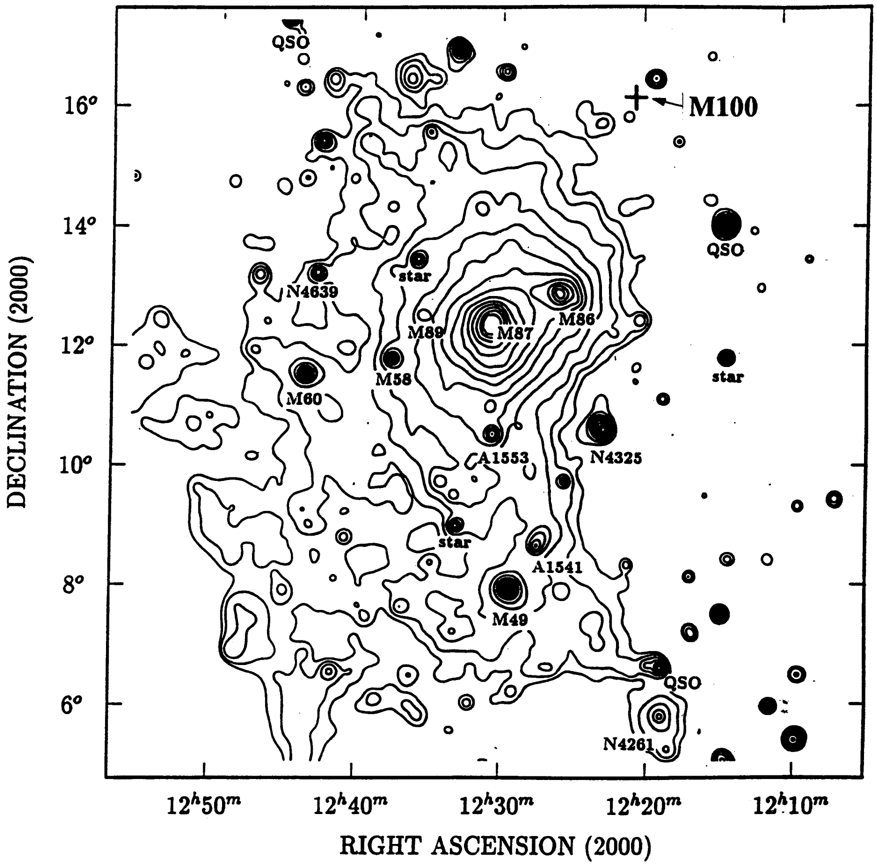

FIG. 2.—Position of M100 in the X-ray Virgo cluster. The *ROSAT* map is from Böhringer et al. (1994).

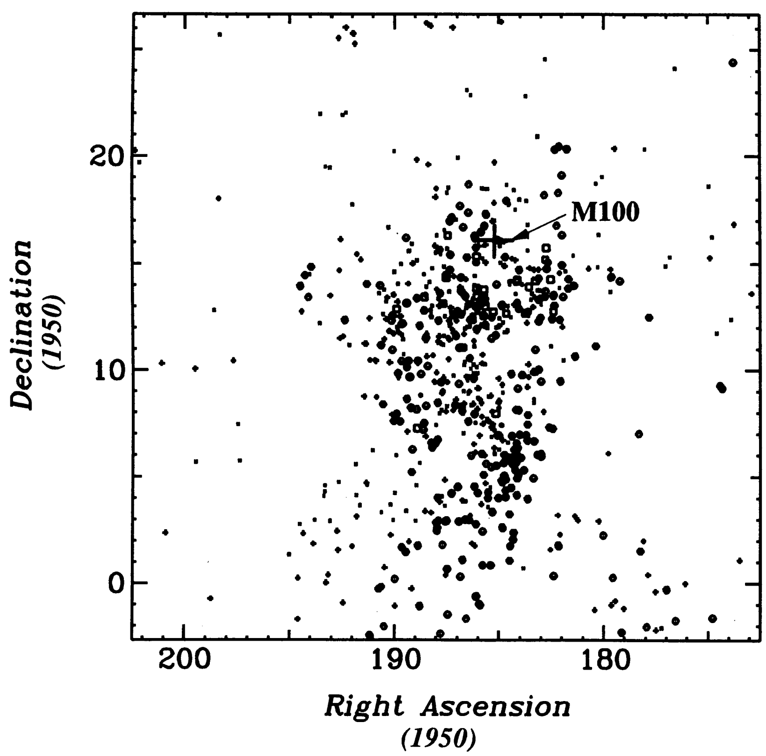

FIG. 3.—Galaxies in the CfA Redshift Catalog (Huchra 1994) in the indicated interval of right ascension and declination and with velocities between -1000 and 2500 km s^{-1}. All objects with measured redshifts in this region are plotted.

the dwarf galaxies and the treatment of the obviously background Virgo West complex (Huchra 1988). Because we see no particular reason to exclude the dwarf galaxies, we adopt the value of 1150 ± 51 from Huchra (1988) which includes the dwarfs but excludes the known background members of Virgo W. We consider this value to be the best estimate, but adopt a 7% uncertainty as the standard error for calculations below. We also point out once again that M87 is at the center of the cluster's hot X-ray gas (Fig. 2) and considered to be at the cluster's center of mass. Its heliocentric velocity is 1292 ± 10 km s^{-1}.

There are two prescriptions for correction to the centroid of the Local Group that give slightly different answers. The IAU correction is -77 km s^{-1} while the correction preferred by Sandage and Tammann is that of Yahil et al. (1977). To be consistent with the peculiar motion determinations below (whole values depend as the reflex of the LG correction applied), we adopt the IAU correction to give a velocity for Virgo corrected to the centroid of the Local Group of 1073 ± 50 km s^{-1}.

A model fit to the TF relation for 308 spiral galaxies in the Local Supercluster by Aaronson et al. (1982a) yielded 331 ± 41 km s^{-1} for the infall of the Local Group into the mass concentration centered on Virgo. The model is analogous to that for Galactic rotation in that there is a local standard of rest, which is a pattern velocity constant on shells of constant radius from the Virgo cluster (250 km s^{-1} locally), and a local random velocity (80 km s^{-1} in the Virgo direction). Subsequent work by Tonry, Dressler, & Luppino (1992) with more accurate distances from surface brightness fluctuations confirm that result, yielding 340 ± 80 km s^{-1} (90% confidence limits). Jerjen & Tammann (1993) obtained 240 ± 40 km s^{-1} for the infall velocity from an analysis of more distant clusters (see also Sandage & Tammann 1990). Han & Mould (1990) argue that a still lower estimate by Faber & Burstein (1988) (85–133 km s^{-1}) results from attributing a further significant reduction of the Hubble velocity of Virgo to the tidal compression of the Local Supercluster by the Great Attractor. Averaging the first three estimates and combining this with the mean observer velocity of 1073 ± 75 km s^{-1}, we find that at the distance of Virgo, the expansion rate is 1380 ± 90 km s^{-1}. This is consistent with Han and Mould's more detailed model for the TF data; they obtained 1422 ± 43 km s^{-1}. We treat this as a confirmation, rather than a separate constraint.

The Hubble constant we derive from the cosmological redshift of Virgo is $H_0 = 81 \pm 11$ km s^{-1} Mpc^{-1}. The uncertainty is derived from the distance and velocity uncertainties taken in quadrature. There is an additional uncertainty arising from the extended nature of the Virgo cluster.

4. EXPANDING PHOTOSPHERES AND SUPERNOVA 1979C

Galaxy distances can be inferred from the expansion of Type II supernovae (SNs) measured photometrically and kinematically. This techniques is referred to as the expanding photospheres method (EPM). There are now four galaxies with Cepheid distances whose Type II SNs yield EPM distances (Schmidt et al. 1994). They are the LMC (49 ± 3 kpc from SN 1987A), M81 (no useful result because of the peculiarity of SN 1993J[14]), M101 ($7.4^{+1}_{-1.5}$ Mpc from SN 1970G), and M100 (15 ± 4 Mpc). Other primary distances are 51 ± 3 kpc for the LMC (Feast 1991; M. Feast 1994, private communication), and 7.5 Mpc for M101 (Kelson et al. 1995).

The distance of M100 has been inferred from the expansion of SN 1979C (Schmidt et al. 1994). Their result, 15 ± 4 Mpc, is fully consistent with the Cepheid distance for M100, but is limited mainly by the large and uncertain apparent extinction of the supernova.

The distance ratio PL/EPM is 1.02 ± 0.08 for the LMC, $1.01^{+0.23}_{-0.17}$ for M101, and 1.13 ± 0.28 for M100. These constraints, taken together without any weighting, amount to 90% confidence that empirical recalibration of EPM distances will be limited to multiplicative factors in the interval (0.88, 1.26). The relation of the data to this interval is shown in Figure 4. Two more points can be anticipated in Figure 4 from discovery of Cepheids in galaxies under study with *HST* in Cycle 4.

Thus there is no evidence that any empirical recalibration of EPM is required at present by the Cepheid data. EPM provides independent and consistent constraints on the Hubble constant, currently yielding $H_0 = 73 \pm 11$ km s^{-1} Mpc^{-1} (Schmidt et al. 1994).

5. SUPERNOVA IA STANDARD CANDLES

The Hubble diagram for Type Ia SNs at maximum light is discussed by Sandage & Tammann (1993). The mean value of V(max) for 6 well observed Type Ia SNs in the Virgo cluster is 12.13 ± 0.14 mag. Scaling the prototypical SN 1973C from 4.8 ± 0.3 Mpc in IC 4182 to our Virgo distance of 17 ± 2 Mpc, implies a visual magnitude of 12.01 ± 0.25 mag (Jacoby & Pierce 1994). The same calculation for SN 1972E in NGC 5253 (Sandage et al. 1994) yields 11.69 ± 0.25 mag, which would therefore appear to have been an unusually luminous event. Hamuy et al. (1995) assert that its high luminosity is related to its slow decline rate (Phillips 1993).

Like the Type II SNs, the Type Ia SNs offer a way to extend our knowledge of the expansion rate from the Local Supercluster, where the high density decelerates the expansion, to the freely expanding region outside it. The new estimate of Type Ia absolute magnitudes based on the six Virgo supernovae

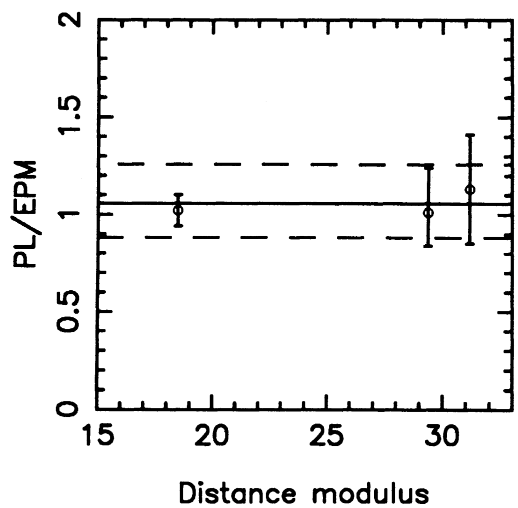

FIG. 4.—Three calibration checks on the expanding photospheres method from Cepheid distances. The data points are the LMC (SN 1987A) M101 (SN 1970G) and M100 (SN 1979C). The dashed lines enclose 90% confidence limits on the ratio of EPM to Cepheid distances.

[14] Schmidt et al. (1993) obtain 2.4 ± 0.4 Mpc. Wheeler et al. (1993) find a distance of 4.2 ± 0.6 Mpc for M81. The Cepheid distance (Freedman et al. 1994b) is 3.6 ± 0.3 Mpc. But the available photospheric models are not appropriate for this peculiar supernova.

permits a determination of H_0 from the 21 galaxies[15] at redshift exceeding 3000 km s^{-1} collated by Sandage & Tammann (1993) and Tammann & Sandage (1995). This yields $H_0 = 71 \pm 7$ km s^{-1} Mpc^{-1} plus an extra uncertainty arising from the extended nature of the Virgo cluster. Addition to this Virgo supernova calibration of SN 1937C and SN 1972E, would yield $H_0 = 69$. The Magellanic type galaxy IC 4182 and the amorphous galaxy NGC 5253 are not necessarily appropriate calibrators, however (van den Bergh & Pazder 1992).

Our results are consistent with the rediscussion of Type Ia SNs by Reiss, Press, & Kirshner (1994), who find $H_0 = 67 \pm 7$ km s^{-1} Mpc^{-1}, but inconsistent with the conclusion of Sandage et al. (1994) who find $H_0 = 55 \pm 8$ km s^{-1} Mpc^{-1} by calibrating V(max) with Cepheid distances for IC 4182 and NGC 5253. The gap could be bridged if the mean Virgo supernovae were 19 Mpc distant (which is not ruled out by the Virgo models considered in the Appendix), and if accounting for the peak-luminosity decline-rate relation results in a 15% increase in H_0 (Hamuy et al. 1995).

Further work will sharpen Type I SNs as tools for distance measurement, including more attention to the correlation of V(max) with decline rate and dependence of V(max) on galaxy type. A future calibration will benefit from additional Cepheid distances of both field galaxies and clusters such as the Fornax cluster.

6. THE TULLY FISHER RELATION FOR CLUSTERS

Mould et al. (1991, 1993) present I-band TF relations in an all-sky sample of 22 clusters of galaxies reaching 7500 km s^{-1}, and Aaronson et al. (1985) provide a pioneering study of 10 Arecibo clusters in the H band within the distance of the Hercules cluster. The Virgo cluster materially adds to the existing field galaxy calibration of the TF relation (Freedman 1990). With the addition of the M101 group galaxies to the Freedman calibrators, the total number of galaxies contributing to the combined H-band calibration summarized in Table 1 is 24. The equation of the regression line shown in Figure 5 is

$$H^{abs}_{-0.5} = -21.32 - 9.53[\log \Delta V(0)_{20} - 2.5] ,$$

where $\Delta V(0)_{20}$ is the 21 cm profile width and $H^{abs}_{-0.5}$ is a measure of the infrared flux. The quantities are fully defined in the original references. The intercept in this regression is 0.09 and 0.28 ± 0.12 mag brighter than those obtained, respectively, by Aaronson et al. (1989) and Freedman (1990). The *HST* Key Project will effectively double the number of calibrators in Figure 5 when completed. With the new Virgo distance the calibration relation for I-band Tully-Fisher becomes:

$$I^{abs} = -20.70 - 9.77[\log \Delta V(0)_{20} - 2.5]$$

The value of the Hubble constant that follows from applying these calibrations to clusters[16] beyond 4000 km s^{-1}, neglecting the effect of perturbations to the Hubble flow and the Virgo depth uncertainty, is $H_0 = 86 \pm 11$ km s^{-1}. If we exclude clusters within 45° of the Great Attractor (Lynden-Bell et al. 1988) (and its antipode), noting the evidence for large scale flows (Mathewson, Buchhorn, & Ford 1993; Mathewson & Ford 1994), we obtain $H_0 = 82 \pm 11$ km s^{-1} Mpc^{-1}. Again, there is an additional uncertainty arising from the extended nature of the Virgo cluster.

In addition to the depth of the Virgo cluster, which introduces an artificial scatter into the relation in Figure 5, there is the possibility that the TF relation is different in clusters and the field (Bernstein et al. 1994; see Han, Mould, & Bothun 1989). Further observations of field TF calibrators with *HST* will address these issues.

TABLE 1

CALIBRATION OF THE INFRARED TULLY-FISHER RELATION

Galaxy	$\Delta V_{20}(0)$	$H^{abs}_{-0.5}$
N4178	298	−20.88
N4192	476	−23.25
N4206	318	−20.68
N4294	252	−20.25
N4380	329	−21.25
I3322A......	296	−20.28
N4450	389	−22.97
N4498	226	−20.26
N4501	597	−23.88
N4519	304	−20.28
N4532	271	−20.58
N4535	423	−22.57
N4651	461	−22.37
N4654	382	−22.23
N4698	460	−22.63
N4758	211	−19.80
M33.........	205	−20.12
M31.........	540	−23.49
N300........	235	−19.50
N2403	265	−21.05
M81.........	450	−23.42
N5204	155	−19.23
N5585	211	−19.38
HoIV	106	−17.04

NOTES.—Sources: Aaronson et al. 1982b; Aaronson et al. 1980b; Freedman 1990.

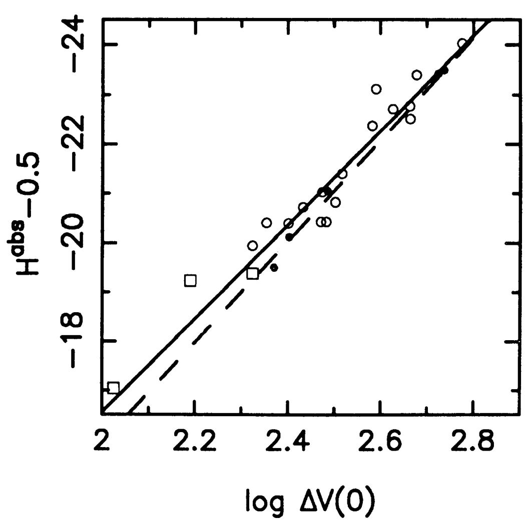

FIG. 5.—Calibrators of the Infrared Tully-Fisher Relation. *Solid symbols:* Freedman (1990); *open circles:* Virgo galaxies from Aaronson et al. 1982b; *boxes:* members of the M101 group. The dashed line is the calibration of Freedman (1990).

[15] The supernovae selected by this cut in redshift are 1959C, 1961D, 1962A, 1962E, 1966K, 1969C, 1968E, 1970J, 1972H, 1972J, 1973N, 1974J, 1975O, 1976J, 1990af, 1991ag, 1992P, 1992ae, 1992aq, 1992bc, and 1992bo.

[16] Sources for the Tully-Fisher data on these clusters are given in § 6.

7. OTHER SECONDARY DISTANCE INDICATORS

7.1. *Surface Brightness Fluctuations*

Tonry et al. (1990) and Ciardullo, Jacoby, & Tonry (1993) have measured surface brightness fluctuations (SBF) in 11 Virgo galaxies. Employing their current calibration, whose zero point is based on early type galaxies in the Local Group:

$$\bar{M}_I = -1.50 + 4(V-I - 1.15)$$

where M_I is the absolute magnitude of a galaxy's SBF in the I band and $V-I$ is the color of the galaxy, one obtains a distance of 15.3 $\pm$ 1.1 Mpc. Adjusting the zero point to the 11% larger Virgo distance we find from Cepheids, one can then examine the expansion rate of the most distant galaxies in the available sample. J. Tonry (1994, private communication) lists three galaxies with SBF measurements with $v_{\rm CMB} > 4000$ km s^{-1}. These yield $H_0 = 84 \pm 16$ km s^{-1}.

It is premature to modify the current calibration on the basis of a Virgo distance which is more uncertain than the distances of Local Group galaxies now employed by Tonry. But we note (1) that groups of early type galaxies with Cepheid distances will provide such a calibration and (2) that when we reach out to large distances with SBF, we obtain constraints on H_0 consistent with those from other secondary distance indicators.

7.2. *The Globular Cluster and Planetary Nebula Luminosity Functions*

Tammann (1988) has used measurements of the globular cluster luminosity function (GCLF) to derive a distance modulus of 31.7 mag for the Virgo cluster. Secker & Harris (1993) argue that the data are compatible with a modulus of 30.9 mag. The M100-based Virgo distance modulus by Freedman et al. of 31.15 $\pm$ 0.36 mag lies between these extremes. Study of a larger and more distant sample of galaxies to investigate the GCLF more fully will benefit from the high resolution of WFPC2. Since the method has not yet been applied beyond the Virgo cluster this method does not offer us a significant constraint on the global value of H_0 at this stage.

A distance of the Virgo cluster of 17 $\pm$ 3 Mpc is consistent with that found by Jacoby et al. (1992) from the planetary nebula luminosity function (PNLF), 15.4 $\pm$ 1.1 Mpc. Like the GCLF, the PNLF is currently limited in application to the Local Supercluster. With our current focus on applying secondary distance indicators at larger redshifts, we do not consider the PNLF further at present.

8. THE COMOVING FRAME AT THE COMA CLUSTER

TF data place Coma 3.69 $\pm$ 0.16 mag behind Virgo according to Aaronson et al. (1986), and (D_n, σ) data yield 3.74 $\pm$ 0.12 mag according to Faber et al. (1985). Jerjen & Tammann (1993) obtain 3.80 mag. These empirical uncertainties are the dominant ones in extending Virgo's distance in Mpc to Coma. The significantly larger redshift of the spirals than the ellipticals in Coma is a 4% effect of lesser importance, as is the evidence that Coma spirals partake in the Hubble flow, unlike the early-type galaxies (Bernstein et al. 1994). The redshift of Coma is $v_{\rm hel} = 6942 \pm 73$ km s^{-1} (Zabludoff et al. 1993). In the reference frame of the cosmic microwave background $v_{\rm CMB} = 7197 \pm 73$ km s^{-1}. Freedman et al. (1994a) employed this ratio to derive the Hubble constant. Mould et al. (1993) fit a number of models to the velocity field within 7500 km s^{-1} and conclude that the expansion rate of the comoving frame is 7170 $\pm$ 125 km s^{-1} at the distance of Coma. None of these details significantly modify the Hubble constant from Coma derived by Freedman et al. of $H_0 = 77 \pm 16$ km s^{-1} Mpc^{-1}.

In a provocative paper Turner, Cen, & Ostriker (1992) have questioned whether the classical approach to the extragalactic distance scale is capable of measuring a global value of H_0 in the presence of a velocity field which exhibits large-scale flows. The results of their numerical experiments can be summed up in the following alarming illustration: "Even if the local expansion rate is known to be 80 $\pm$ 8 km s^{-1} Mpc^{-1} out to 30 h^{-1} Mpc in the North Galactic Cap, the 95% confidence limits on the true global value of H_0 is 50–128 km s^{-1} Mpc^{-1} in a CDM model."

With WFPC2 we do not expect to be able to measure distances directly with Cepheids very far beyond the Virgo cluster, where the expected rms difference between local and global H_0 is 45% in current CDM. The subject of the present paper, however, is the calibration of secondary distance indicators whose effective range extends beyond the Coma cluster. At Coma the same rms difference has fallen from 45% to 3% in CDM according to Turner et al.

Empirical evidence that real velocity fields present no larger problem than these calculations suggest is provided by:

1. An all-sky survey of Tully-Fisher distances to clusters of galaxies;
2. An all-sky survey of brightest cluster galaxies (Lauer & Postman 1994);
3. The EPM data set.

These data are collected in Figure 6. Sources of TF cluster data are Aaronson et al. (1986), Mould et al. (1991, 1993), and Han & Mould (1992). The data have not been normalized to a common value of H_0, although Figure 6 is very similar, whichever of $H_0 = 82$ (§ 6), 73 (§ 4), or 80 km s^{-1} Mpc^{-1} (Lauer & Postman) one adopts as a common value.

We can hypothesize a "bubble model" in which $\delta H/H_0 \sim 0.5$, that is, $H_0 = 75$ km s^{-1} Mpc^{-1} within the distance of the Coma cluster and $H_0 = 50$ outside the radius. Figure 6 shows clearly that these data rule out a model with such a large difference between local and global H_0. Indeed, Lauer & Postman (1992) conclude that $\delta H/H_0 < 0.07$ within the volume shown in Figure 6.

Such a model is also heavily constrained by the isotropy of the cosmic microwave background on 1° scales. One hundred

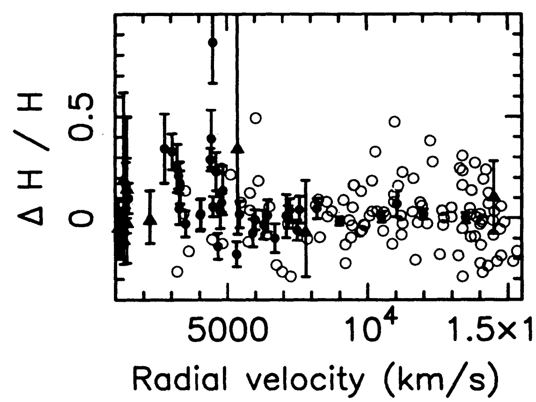

FIG. 6.—Deviations from a uniform Hubble flow. *Solid circles:* clusters of galaxies with Tully-Fisher distances. *Solid triangles:* EPM data of Schmidt et al. (1994). *Open symbols:* brightest cluster members from Lauer & Postman (1994). There is no evidence that a different value of the Hubble constant pertains inside and outside the distance of the Coma cluster at $v_{\rm CMB}$ = 7200 km s^{-1}.

Mpc, which is approximately the radius of the volume enclosing Coma, corresponds to 1° (12′) on the surface of last scattering for $\Omega = 1$ (0.2). The requirement that $\delta H/H_0 \sim 0.5$ in a "bubble model" of this type implies a larger density perturbation (3 times) than is represented by the Great Attractor (Lynden-Bell et al. 1988). Bertschinger, Gorski, & Dekel (1990) show that a Great Attractor would evolve from $\Delta T/T = 1.7 \times 10^{-5}$ in an $\Omega = 1$ universe. Schuster et al. (1993) have measured $\Delta T/T < 1 \times 10^{-5}$ on 1°.5 scales. A low-density universe would relax these constraints considerably (Fullana, Saez, & Arnau 1994).

9. DISCUSSION

There are only two independent constraints on H_0 in the preceding sections. The first is contained in § 4 (EPM) and the second in §§ 3, 5, and 6, involving the additional assumption that we have successfully constrained the distance of the Virgo cluster. The discussion of EPM in § 4 appears to rule out $H_0 < 73/1.26 = 58$ km s^{-1} Mpc^{-1} at the 90% confidence level. From a similar upper bound our verification of the EPM calibration yields $58 < H_0 < 89$ km s^{-1} Mpc^{-1} with 90% confidence.

The constraint which M100 puts on the distance of the Virgo cluster is a more complex issue. Associating M100 with a cluster core of a certain structure, Freedman et al. (1994a) obtain $H_0 = 80 \pm 17$ km s^{-1} Mpc^{-1}. Models of the cluster discussed in the Appendix consider the distances of M100 and NGC 4571 as a constraint on the cluster distance. The models assert that the cluster distance is *probably* less than 19 Mpc; i.e., they yield a constraint which is no stronger than that adopted by Freedman et al. They rule out a mean cluster distance exceeding 22 Mpc at the 95% confidence level. The other tail of the distribution ($d < 11$ Mpc) is similarly excluded. These considerations (and velocity uncertainties are negligible by comparison) yield $55 < H_0 < 105$ km s^{-1} Mpc^{-1} with 90% confidence.

Formally, under these two conditions H_0 lies in the interval (50, 100) with more than 99% confidence, but it is not hard to find other scenarios to relax this constraint significantly. Suppose that:

1. The early-type galaxies in Virgo are associated with component B (the smaller one) of the model;
2. The infall velocity of the Local Group is actually 2 σ lower than estimated in § 3, i.e., 220 km s^{-1} (Tammann & Sandage 1985).

Even these assumptions, however, require $H_0 > 53$ km s^{-1} Mpc^{-1}. In Model 8 component B is closer than 24.5 Mpc with 95% confidence. This illustrates that we have a strong lower limit on H_0.

It is not a completely unequivocable limit, however. To exemplify this, consider one further possibility, whose likelihood it is hard to quantify, which might conceivably release the Hubble constant from the present Virgo cluster constraints:

3. The velocity of component B with respect to the centroid of the Local Group is that of M49, i.e., 847 km s^{-1}.

This would allow $H_0 = 44$ km s^{-1} Mpc^{-1}. We exclude this possibility, however, as the redshift of M49 (the brighter of the two gE's in Virgo) does not seem to be relevant to Virgo cluster calibrators of any of the secondary distance indicators we are using here.

We can see from the foregoing that we are dealing with a complex situation in Virgo (Jacoby et al. 1992); constraints on H_0 will therefore inevitably remain looser than those which can be obtained from a simpler cluster such as Fornax.

The present discussion contrasts strongly with that of Pierce et al. (1994) who obtain $H_0 = 87 \pm 7$ km s^{-1} Mpc^{-1}. The error budget in the Hubble constant determination tabulated by Freedman et al. (1994a) contains 12 terms of which the dominant ones are uncertainties in the extinction of the Cepheids, and the extended nature of the Virgo cluster. Each of these uncertainties is as large as the uncertainty in H_0 quoted by Pierce et al. Pierce et al. have given little consideration to these matters, concentrating, appropriately enough since they detected only three Cepheids in NGC 4571, on the width of the PL relation as the primary uncertainty in their results. We assert that, contrary to the optimistic view of Pierce et al., the confidence limits that can be put on H_0 at this time are those discussed herein.

10. SUMMARY

In summary, the distance of M100 impacts the extragalactic distance scale in two ways, first in its own right as a calibrator of EPM, and second, by providing the distance of the Virgo cluster for the TF relation, the (D_n, σ) relation, the Type Ia SN standard candle, and surface brightness fluctuations. With the confirmation of the EPM calibration provided by SN 1979C, EPM yields $H_0 = 73 \pm 11$ km s^{-1} Mpc^{-1}. Assuming a Virgo cluster distance of 17 ± 3 Mpc, the other secondary distance indicators yield $H_0 = 80 \pm 16$ km s^{-1} Mpc^{-1}. The uncertainty in the first case is dominated by the observational data pertaining to SN 1979C. In the second case the uncertainty is dominated by the depth of the Virgo cluster.

In combination these results strengthen the conclusion of Freedman et al. (1994a) that $H_0 = 80 \pm 17$ km s^{-1} Mpc^{-1}. The 95% confidence limits on H_0 are the interval (50, 100) km s^{-1} Mpc^{-1}.

The key project aims to secure the distances of two more Virgo galaxies, which will markedly reduce the uncertainty in the mean cluster distance. A total of 20 galaxy distances is being sought in the key project to secure the calibration of secondary distance indicators in general, and thus to reduce the uncertainty in the Hubble constant to 10%.

The key observations discussed herein were made with the *Hubble Space Telescope*, which is managed for NASA by the Space Telescope Science Institute. We thank STScI director, Bob Williams, for encouraging us to observe M100 early in the life of the Key Project to determine the extragalactic distance scale. We thank the WFPC2 team for furnishing an instrument which is up to the job. We acknowledge NASA grant 2227 from STScI.

TABLE 2

VIRGO CLUSTER MODELS

Model Number	d (Mpc)	r (Mpc)	Comment
1........	17	3.5	Fits PT data
2........	A: 16	2	A is 2/3 total cluster
	B: 22	2	B is 1/3
3........	16	1	
4........	A: 16	1	Fits PT data
	B: 22	1	A B (2:1 as above)
5........	19	3.5	Fits constraints 14% of time
6........	22	3.5	Fits constraints 5% of time
7........	A: 16.5	1	Fits constraints 16% of time
	B: 22.5	1	
8........	A: 18.5	1	Fits constraints 4% of time
	B: 24.5	1	

APPENDIX

Evidence for substructure in the Virgo cluster is discussed by Bingelli et al. (1987), Huchra (1988), Pierce & Tully (1988, hereafter PT), and Tonry et al. (1990). To quantify our discussion of the uncertainties arising from this substructure we have generated a number of idealized models[17] of the Virgo cluster with the following general properties:

1. The cluster is located at a mean distance d from the observer.
2. Galaxy distances are normally distributed from the cluster center with variance r^2.
3. Errors in distance modulus of 0.3 mag arise from use of the Tully-Fisher (TF) relation.

With this prescription it is possible to explore the parameter space of models which fit the distribution of Virgo galaxy distances inferred by PT (see Table 2). Inspection of Figure 7 shows that within the small number statistics of the PT data Model 1 with a large value of r (3.5 Mpc) is a satisfactory fit. Smaller and larger values of r are not good fits.

Two component models are motivated both by the appearance of the distribution of the PT data in Figure 7 and by examination of the much larger TF database of Fouqué et al. (1990). In Fouqué's data the mean TF distance of spirals within 2° of M49 is 0.67 ± 0.20 mag larger than that of spirals within 2° of M87. M87 and M49 are the two brightest ellipticals in Virgo. The simplest two component model to provide a satisfactory fit to the data in Figure 7 is Model 4.

We now experiment by increasing d and calculating the probability that, of two galaxies drawn from the distribution, one will be closer than 14.9 ± 1.2 Mpc and the other closer than 17.1 ± 1.8 Mpc. In Model 5 (a one component model) we see that, if d is increased to 19 Mpc, the probability that these constraints will be satisfied is approximately 14%. We can confidently rule out Model 6 with $d = 22$ Mpc.

Models 7 and 8 quantify the upper limits on two component models. We can confidently rule out Model 8 with its mean distance $d = 20.5$ Mpc.

[17] These models assume line-of-sight distances; no consideration is given to the angular distribution of Virgo galaxies.

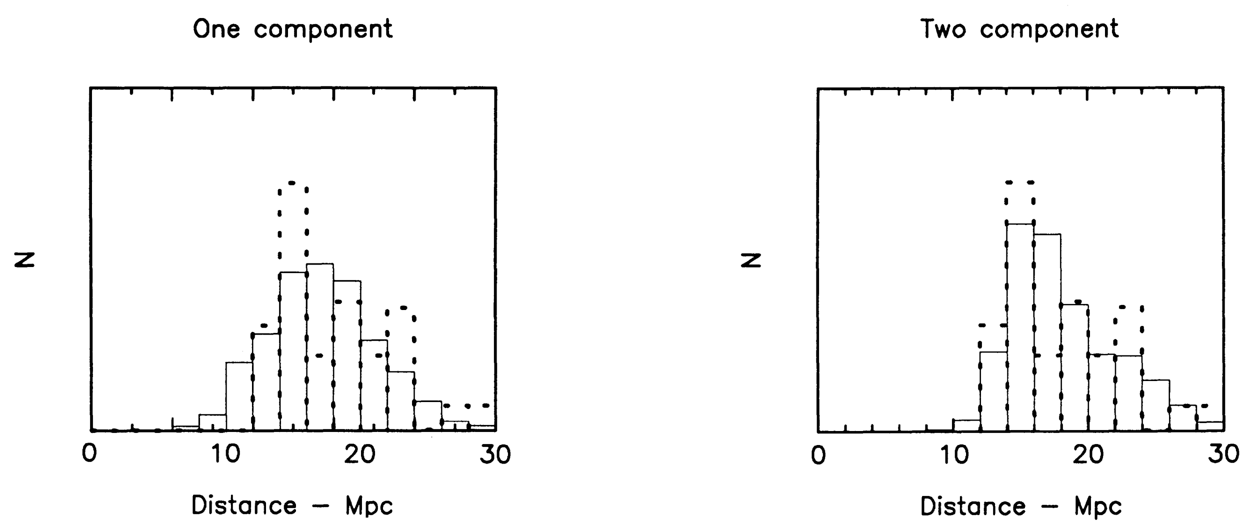

FIG. 7.—Monte Carlo realizations of Model 1 (*solid curve*) compared with the scaled distribution of distances tabulated by Pierce & Tully (1988) (*dashed curve*). Lower graph: model 4.

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