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The Hubble Parameter

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ABSTRACT. Distance determinations to individual galaxies, groups, and clusters are critically reviewed. All modern distance determinations have been reduced to a common and internally consistent system. These distances are then used to discuss the present status of the extragalactic distance scale and of the Hubble Parameter, H_0. It is shown that the classical distance-scale "problem" starts quite abruptly at $D \gtrsim 3$ Mpc. It is emphasized that the reasons for this discrepancy are entirely independent of difficulties associated with large-scale deviations from a smooth Hubble flow. From eight different techniques the mean distance modulus of the Virgo cluster is found to be $(m-M)_0 = 31.0 \pm 0.15$ ($D = 15.8 \pm 1.1$ Mpc). Twelve determinations of the difference between the distance moduli of the Coma and Virgo clusters yield $\Delta(m-M)_0 = 3.71 \pm 0.05$ mag and hence a Coma distance modulus $(m-M)_0 = 34.71 \pm 0.16$ ($D = 87 \pm 6$ Mpc). Combining this distance with the Coma cluster's cosmological velocity of 7210 km s^{-1} yields a value $H_0(\text{local}) = 83 \pm 6$ km s^{-1} Mpc^{-1}. From the velocity-distance relation for the brightest galaxies in clusters of Bautz–Morgan types I and I-II it is found that $H_0(\text{global})/H_0(\text{local}) = 0.92 \pm 0.08$, in which "local" refers to northern clusters with $V_0 < 10{,}000$ km s^{-1}. In other words, the cluster data do not show a statistically significant difference between the local and global values of the Hubble parameter. If one nevertheless adopts $H_0(\text{global})/H_0(\text{local}) = 0.92 \pm 0.08$ then one obtains $H_0(\text{global}) = 76 \pm 9$ km s^{-1} Mpc^{-1}. This observed value of H_0 differs at the $\sim 3\sigma$ level from that predicted by theories of stellar evolution in conjunction with canonical models of the Universe with $\Omega = 1$ and $\Lambda = 0$.

1. INTRODUCTION

Because galaxies are so far away, the distance gauges within them are dim and difficult to observe. Measurements of these distance indicators are therefore often subject to large random and systematic errors. Furthermore, the luminosities of "standard" candles might be affected by differences in age, evolutionary history, and chemical abundance. In attempting to determine the extragalactic distance scale it is therefore prudent to minimize the effects of possible systematic errors by using as many independent types of distance indicators as possible. An additional difficulty, which has only been fully appreciated in recent years, is that large deviations from a smooth Hubble flow make it difficult to establish the relationship between velocities and distances of individual galaxies at intermediate redshifts.

Recent reviews of the extragalactic distance scale, and of the techniques used to determine it, are given in Rowan-Robinson (1985, 1988), Madore and Tully (1986), van den Bergh and Pritchet (1988), van den Bergh (1989), Visvanathan (1990), Huchra (1992), and Jacoby et al. (1992). The Jacoby et al. paper emphasizes modern techniques of distance determination, whereas the present investigation focuses mainly on the numerical values for the distances to individual galaxies, groups and clusters.

As the Universe expands the ratio of redshift to distance changes. Hence the instantaneous value of this ratio drifts (albeit very slowly) with time. It therefore seemed preferable to call H_0 the Hubble parameter rather than the Hubble constant.

2. DISTANCES TO LOCAL GROUP GALAXIES

Distances to the nearby members of the Local Group are important stepping stones along the path that leads to the determination of the extragalactic distance scale. A comprehensive discussion of the distances to Local Group members derived prior to 1989 has been given by van den Bergh (1989). Since that time a number of new distance determinations have been published which are discussed below.

2.1 Distances to the Magellanic Clouds

Eastman and Kirshner (1989) have used an expanding photosphere model to obtain a true distance modulus (m

TABLE 1
Recent Distance Determinations for the Magellanic Clouds

Method	Reference	$(m-M)_0^{LMC}$	$(m-M)_0^{SMC}$
Cepheids BVI	Feast (1988)	18.52	18.83
Cepheids JHK	Laney & Stobie (1988)	18.52	
Cepheids 1μm	Visvanathan (1989)	18.42	18.83
Mira variables	Feast (1988)	18.28	18.58
LP variables	Hughes & Wood (1990)	18.64	
Novae	Capaccioli *et al.* (1990)	18.71	
Planetary nebulae	Ciardullo & Jacoby (1992)	18.44	18.79
RR Lyrae NGC 121	Walker (1988a)		18.86[a]
RR Lyrae NGC 1786	Walker (1988a)	18.44[a]	
RR Lyrae NGC 1841	Walker (1990)	18.12[a]	
RR Lyrae NGC 2210	Walker (1988a)	18.42[a]	
RR Lyrae NGC 2257	Walker (1988a)	18.41[a]	
Field RR Lyrae	Hazen & Nemec (1992)	18.66[a]	
SN 1987A	Eastman & Kirshner (1989)	18.47	
SN 1987A	Panagia *et al.* (1991)	18.52	
SN 1987A	Hanuschik & Schmidt-Kalar (1991)	18.49	
	Unweighted mean	18.47	18.78

[a] M_V(RR) = +0.6 assumed

TABLE 2
Distances to Selected Local Group Galaxies

Galaxy	$(m-M)_0$	D(kpc)
LMC	18.45 ± 0.1	49
SMC	18.80 ± 0.15	58
NGC 6822	23.66 ± 0.2	540
NGC 185	23.96 ± 0.25	620
NGC 147	24.09 ± 0.25	660
M31	24.3 ± 0.1	725
M32	24.3	725
NGC 205	24.3	725
IC 1613	24.42 ± 0.13	765
M33	24.5 ± 0.2	795

$-M)_0=18.45\pm0.28$ for SN 1987A. (All observational errors quoted in the present review are standard deviations.) Adopting an inclination of 27°, and a position angle for the line of nodes of the fundamental plane of the Large Cloud of 170°, together with the assumption that the supernova exploded in the disk of the LMC (Jacoby et al. 1992), yields a distance modulus of $(m-M)_0=18.47\pm0.28$ for the center of the Large Magellanic Cloud (LMC). Using a similar technique, Hanuschik and Schmidt-Kaler (1991) derive $(m-M)_0=18.47\pm0.18$ for SN 1987A, which corresponds to $(m-M)_0=18.49$ (49.9 kpc) for the center of the LMC. A similar correction applied to the distance of SN 1987A derived from its circumstellar ring by Panagia et al. (1991), but see *caveats* by Dwek and Felten (1992), yields a distance modulus $(m-M)_0=18.52\pm0.13$ for the center of the LMC. From a comparison of the maximum magnitude vs rate of decline relation for novae in the Magellanic Clouds and the Galaxy, Capaccioli et al. (1990) obtain $(m-M)_0=18.71^{+0.27}_{-0.32}$. A rather similar value, which these authors obtain from the assumption that all novae have the same magnitude at 15 days past maximum, will *not* be used in the present review because M31 novae Nos. 1, 2, and 3 of Arp (1956) showed that fast novae are systematically fainter than slow novae at 15 days past maximum light.

From a comparison of 1.05 μm measurements of Cepheids in the LMC and SMC with those of Cepheids in Galactic open clusters, Visvanathan (1989) obtains $(m-M)_0=18.42\pm0.02$ for the LMC and $(m-M)_0=18.83\pm0.04$ for the SMC.

Walker (1990) has observed the RR Lyrae stars in the LMC globular cluster NGC 1841. For these objects he finds $\langle V\rangle=19.31\pm0.02$ and $E(B-V)=0.18\pm0.02$. For consistency with van den Bergh (1989), the values $A_V/E(B-V)=3.3$ and $M_V(\mathrm{RR})=+0.6$ will be adopted, yielding $(M-m)_0=18.12$. This value is $\sim$0.4 mag smaller than the mean of the other Large Cloud distance moduli, which are compiled in Table 1. This suggests that either NGC 1841 lies in front of the LMC, or its reddening has been significantly overestimated. It should be noted that two very recent determinations of M_V(RR) based on the Baade–Wesselink technique (Clementini et al. 1992; Carney et al. 1992) yield M_V(RR) Lyrae values that are 0.14 to 0.20 mag *fainter* than our adopted value at [Fe/H]$=-1.4$. On the other hand, Walker (1992) advocates a somewhat *brighter* luminosity for the RR Lyr stars in the LMC. This question will be discussed in more detail in Sec. 2.3.

Hughes and Wood (1990) find a distance modulus $(m-M)_K=18.66\pm0.05$ by comparing the long-period variables in the Large Cloud with those in 47 Tucanae (Hesser et al. 1987). With $\langle E(B-V)\rangle=0.07$ and $A_K=0.34E(B-V)$ this yields $(m-M)_0=18.64\pm0.05$ for the LMC.

Finally Jacoby et al. (1990) obtain a LMC distance modulus $(m-M)_0=18.44\pm0.18$ and an SMC modulus $(m-M)_0=19.09^{+0.25}_{-0.32}$ by comparing the luminosity functions of planetary nebulae in the Clouds with that of planetaries in M31, for which they assumed $(m-M)_0=24.26$ and a Galactic forground reddening $E(B-V)=0.11$. With these values, and $A_{5007}=0.39$ mag, they obtain $(m-M)_{5007}=24.65$. This compares with our adopted values of $(m-M)_0=24.3$ and $E(B-V)=0.07$, which give $(m-M)_{5007}=24.55$ for M31. For the sake of consistency all planetary-nebula distances obtained by Jacoby and his collaborators have therefore been *reduced* by 0.1 mag in this review. After application of this correction, and a small metallicity correction (Ciardullo and Jacoby 1992), the distance moduli derived from planetary nebulae become $(m-M)_0=18.44$ for the LMC and $(m-M)_0=18.79$ for the SMC.

On the basis of the data collected in Table 1, $(m-M)_0^{\mathrm{LMC}}=18.45\pm0.10$ and $(m-M)_0^{\mathrm{SMC}}=18.80\pm0.15$ will be adopted in the subsequent discussion.

2.2 Distances to M31 and M33

Distance determinations to the Andromeda nebula (M31) have recently been reviewed by van den Bergh (1991a). From six modern determinations, $(m-M)_0=24.3\pm0.1$, corresponding to a distance of 725 ± 35 kpc. This value is based on $M_V(\mathrm{RR})=+0.6$, a foreground reddening $E(B-V)=0.07$, and a distance modulus $(m-M)_0=18.45$ for the LMC. Confidence in this distance determination for M31 is strengthened by the fact that Population I distance indicators (Cepheids) and Population II indicators (RR Lyr stars, red-giant branches) give the same distance to the Andromeda nebula.

Recent distance determinations to the Triangulum nebula (M33) have been reviewed by van den Bergh (1991b). From 11 modern distance determinations it is found that $(m-M)_0=24.5\pm0.2$, corresponding to $D=795\pm75$ kpc. The Population I and Population II distance indicators give true unweighted moduli of 24.46 ± 0.10 and 24.67 ± 0.07, respectively, for M33.

2.3 Distances to Other Local Group Members

Distances to the ten most luminous Local Group galaxies outside the Milky Way are summarized in Table 2. The data in this table were mainly drawn from van den Bergh (1989). New data are, however, given for the SMC (see Sec. 2.1), and for NGC 147 and NGC 185. The quoted distance moduli for NGC 147 (Saha et al. 1990) and for NGC 185 (Saha and Hoessel 1990) are based on $M_V(\mathrm{RR})=+0.6$, which is 0.17 mag brighter than the value adopted by Saha and his collaborators. The derived distances to these two objects also depend rather critically on the adopted foreground reddening (Burstein and Heiles 1984). Recently Saha et al. (1992) have used observations of faint RR Lyr stars to obtain a distance to NGC 205 that is 15% greater than that for the Andromeda nebula. In compiling Table 2 it has, however, been *assumed* that M31 and NGC 205 are, in fact, at the same distance. (The twisting of the outer isophotes of NGC 205 might be due to the M31 gravitational tides.) Freedman (1989) has used observations of red giants in M32 to derive a distance that was 100 kpc smaller than that of the Andromeda nebula. Because of suggestive evidence (Schwarzschild 1954) for a tidal interaction between M31 and M32 it has, however, been assumed that these two galaxies are, in fact, located at the same distance. Recently Lee (1992) has suggested that Pritchet and van den Bergh (1987) underestimated the distance of M31 derived from RR Lyr stars. This conclusion was based on the assumption that the RR Lyr variables observed in the halo of M31 are similar to those in the Galactic halo. However, Mould and Kristian (1986) and Pritchet and van den Bergh (1988a) have shown that the dominant stellar population in the halo of M31 is relatively metal rich. As a result, the RR Lyr stars in M31 are, on average, probably metal richer, and hence fainter, than Lee (1992) assumed. The distances for NGC 6822 and IC 1613 listed in Table 2 are from the discussion of Madore and Freedman (1991).

In a recent paper Walker (1992) finds that the RR Lyr stars in the Large Magellanic Cloud are ~0.3 mag brighter than the value suggested by statistical parallax analysis. It therefore seems worthwhile to check if there are any systematic differences between the distances of Local Group galaxies derived from Population II distance indicators (RR Lyr stars, red giants) and the mean-distance moduli of the LMC and SMC (see Table 1), M33 (van den Bergh 1991a), and M31 (van den Bergh 1991b) adopted in the present investigation. The 12 Population II distance moduli included in these sources are found to be 0.03 ± 0.05 mag larger than the adopted means. It is therefore concluded that the Population II distances derived by assuming $M_V(\mathrm{RR})=+0.6$ are, within the accuracy of presently available data, consistent with those derived from a variety of other techniques.

TABLE 3
All Known Local Group Galaxies

Name	α (1950)	δ (1950)	Type	M_V
M31=NGC 224	$00^h\ 40^m.0$	$+41^{\circ}00$	Sb I-II	-21.1
Galaxy	17 42.5	-28 59	Sb/Sc	-20.6[b]
M33=NGC 598	01 31.1	+30 24	Sc II-III	-18.9
LMC	05 24	-69 50	Ir III-IV	-18.1
M32=NGC 221	00 40.0	+40 36	E2	-16.4
NGC 6822	19 42.1	-14 53	Ir IV-V	-16.4
NGC 205	00 37.6	+41 25	Sph	-16.3
SMC	00 51	-73 10	Ir IV/IV	-16.2
NGC 185	00 36.1	+48 04	D Sph	-15.3
NGC 147	00 30.4	+48 14	D Sph	-15.1
IC 1613	01 02.3	+01 51	Ir V	-14.9
WLM	23 59.4	-15 45	Ir IV-V	-14.1
Fornax	02 37.5	-34 44	D Sph	-13.7
And I	00 43.0	+37 44	D Sph	-11.8
And II	01 13.5	+33 09	D Sph	-11.8
Leo I	10 05.8	+12 33	D Sph	-11.7
DDO 210	20 44.2	-13 01	D Ir	-11.5
Sculptor	00 57.5	-33 58	D Sph	-10.7
And III	00 32.6	+36 14	D Sph	-10.3
Psc=LGS 3	01 01.2	+21 37	D Ir	-10.2
Sextans	10 10.5	-01 22	D Sph	-10.0
Phoenix	01 49.0	-44 42	D Ir/D Sph	-9.9
Tucana	22 38.5	-64 41	D Sph	-9.5
Leo II	11 10.8	+22 26	D Sph	-9.4
Ursa Minor	15 08.2	+67 18	D Sph	-8.9
Draco	17 19.4	+57 58	D Sph	-8.6
Carina	06 40.4	-50 55	D Sph	-7.6

[a] D < 1.0 Mpc

[b] Internal absorption of 0.5 mag assumed

Table 3 gives a complete listing of all presently known members of the Local Group, which was operationally defined to consist of all those galaxies with distances <1.0 Mpc. The data were mainly drawn from van den Bergh (1989), which was supplemented by more recent information on the Phoenix and Fornax systems (van de Rydt et al. 1991) and on the Tucana (Lavery and Mighell 1991) and Sextans (Mateo et al. 1991) dwarfs. Revised integrated magnitudes for And I, And II, and And III and for some other dwarf galaxies are from Caldwell et al. (1992).

The Local Group suspects EGB 0427+63 (Hoessel et al. 1988) and UGC-A86 (Saha and Hoessel 1991) have *not* been included in Table 3 because their positions on the sky suggests that they might, in fact, be members of the more distant IC 342-Maffei 1 group (van den Bergh 1971). Recent H II region observations by Miller and Hodge (1992) are consitent with the hypothesis that UGC-A86 is a member of the IC 342 group.

Figure 1 shows the integrated luminosity functions of the Local Group derived from the data in Table 3. It is of interest to note that the luminosity function of the Local Group is apparently still rising at $M_V\simeq-8$, i.e., there is no indication for a low-luminosity cutoff in the galaxian luminosity function.

3. GALAXIES AT INTERMEDIATE DISTANCES

Galaxies and small clusters at intermediate distances (1–10 Mpc) are important rungs on "the distance ladder."

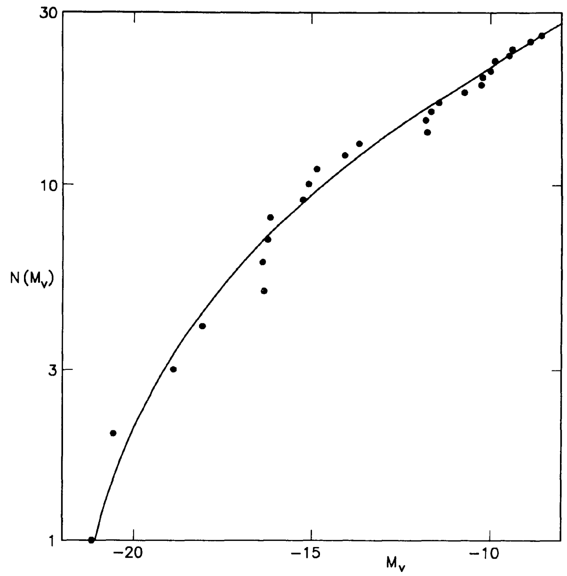

FIG. 1—Integrated luminosity function for members of the Local Group. The curve is a Schechter function with $M_V^* = -22.5$ and $\alpha = -1.1$.

In the following sections particular emphasis will be placed on the determination of distances to those nearby groups of galaxies, such as Sculptor, M81, Centaurus, and Leo, which can be used to calibrate the Tully–Fisher relation, the Faber–Jackson relation, the luminosities of supernovae, etc. Groups and small clusters of galaxies at intermediate distances therefore constitute an important link between the Local Group and distant giant clusters such as Virgo and Coma.

3.1 The Irregular Dwarf Galaxy NGC 3109

NGC 3109=DDO 236 is an edge-on dwarf of type Ir IV-V. This galaxy is of particular importance because it is the least luminous calibrator that is presently known for the Tully–Fisher relation (Pierce and Tully 1992). CCD observations of 21 Cepheids discovered by Sandage and Carlson (1988) have recently been reported by Capaccioli et al. (1992). From a comparison between the period-luminosity relations of NGC 3109 and the Large Magellanic Cloud, Capaccioli et al. obtain $\Delta(m-M)_V=6.90 \pm 0.12$ and $\Delta(m-M)_B=6.79\pm0.18$. Adopting mean reddening values of $E(B-V)=0.07$ and $E(B-V)=0.04$ for the LMC and NGC 3109, respectively, and $A_V=3.3\,E(B-V)$, one obtains $\Delta(m-M)_0=7.00$ from the visual period-luminosity relation and $\Delta(m-M)_0=6.92$ from the blue period-luminosity relation. A value $\Delta(m-M)_0=6.95 \pm 0.15$, combined with an LMC modulus $(m-M)_0 = 18.45\pm0.10$, yields a true distance modulus $(m-M)_0 = 25.4\pm0.18$, corresponding to $D=1.2$ Mpc for NGC 3109. This places NGC 3109, just beyond the (arbitrary) 1.0 Mpc distance limit for Local Group members. (Note that NGC 3109 lies 144° away from M31 on the sky, i.e., it is on the opposite side from the center of mass of the Local Group.) From observations of seven planetary nebulae in NGC 3109, Richer and McCall (1992) determine a distance modulus of 25.7 ± 0.5. After a metallicity correction of -0.3 mag (Jacoby 1992) this becomes 25.4 ± 0.5, which is in excellent agreement with the value obtained from Cepheids. With a distance modulus $(m-M)_0=25.4$ and $B_T = 10.27$ (Carignan 1985), NGC 3109 has $M_B=-15.3$. This is quite similar to $M_B=-15.9$ for the Small Magellanic Cloud, which is classified Ir IV/V. In view of the low luminosity of NGC 3109 its metallicity and dust content (van den Bergh and Pierce 1990) are probably quite low. As a result the internal absorption $A_B=0.67$ adopted by Pierce and Tully (1992) is possibly too high.

TABLE 4
Relation Between Diameter and Depth of Spherical Clusters

Δ(m-M)	cluster diameter
0.2 mag	5°3
0.4	10.5
0.6	15.8
0.8	21.0
1.0	26.2

The dwarf galaxies Sextans A (DDO 75) and Sextans B (DDO 70) may be loosely associated with NGC 3109. The angular separation between Sex A and NGC 3109 is only 21°6. From a comparison of three Cepheids in Sex A observed at 1.05 μm with Cepheids in Galactic open clusters, Visvanathan (1989) finds a distance modulus $(m-M)_0 = 25.27\pm0.17$ ($D=1.1\pm0.1$ Mpc), which is quite similar to the distance of 1.1 Mpc that was obtained above for NGC 3109.

3.2 The Sculptor (South Pole) Group

The Sculptor group, which has a radius of about 10° (Puche and Carignan 1988), consists of NGC 55, NGC 247, NGC 253, NGC 300, NGC 7793, and the Sculptor dwarf irregular galaxy (SDIG) (Laustsen et al. 1977). Inspection of the images of Sculptor group members (Graham 1982) strongly suggests that this small cluster is significantly extended along the line of sight. [From the observed cluster diameter a range of ~0.7 mag in $(m-M)_0$ might be expected (see Table 4).]

By comparing the luminosity functions of carbon stars in NGC 55 and the LMC [for which $(m-M)_0=18.45$ was assumed] Pritchet et al. (1987) find $(m-M)_0=25.66 \pm0.13$ ($D=1.36\pm0.08$ Mpc). This value is probably a slight overestimate because the I-band absorption in the edge-on galaxy NGC 55 is likely to be somewhat higher than it is in the Large Cloud.

From observations of 24 probable globular clusters, Blecha (1986) obtained an estimated distance of 2.4 to 3.4 Mpc for NGC 253. This distance is, however, very uncertain because Blecha's data do not reach below the peak of the globular-cluster luminosity function. An I versus $V-I$ color-magnitude diagram for stars in the halo of NGC 253 by Davidge and Pritchet (1990) suggests that the tip of

TABLE 5
Distance Moduli of Sculptor Group Galaxies

Galaxy	Type	Method	(m-M)$_0$
NGC 45	S IV-V		
NGC 55	Sc or Ir	Carbon stars	25.66 ± 0.13
NGC 247	S IV		
NGC 253	Sc pec	Globular clusters	26.9 - 27.7
		Halo stars	26.1 - 27.1
NGC 300	Sc III-IV	Planetary nebulae	25.85 ± 0.34[a]
		Red giants	25.8
		Carbon stars	25.87 ± 0.15
		Cepheids BV	26.4 ± 0.2
		Cepheids BVRI	26.43 ± 0.1
		Cepheids 1μm	25.72 ± 0.12
			26.0 ± 0.2
NGC 7793	Sc III-IV/IV or IV		

[a] But see caveats in §3.2

TABLE 6
Distance Moduli of M81 Group Galaxies

Galaxy	Method	Reference	(m-M)$_0$
NGC 2403	Cepheids	Freedman & Madore (1988)	27.46 ± 0.24
	Cepheids	McAlary & Madore (1984)	28.15 ± 0.20
NGC 3031	Cepheids	Freedman & Madore (1988)	27.54 ± 0.31
	Planetaries	Jacoby *et al.* (1989)	27.62 ± 0.25
	M supergiants	Humphreys *et al.* (1986)	27.6 ± 0.3
	Fluctuations	Tonry (1991)	27.62 ± 0.15
			27.6 ± 0.15

red-giant branch falls in the range $22.5 \lesssim I \lesssim 23.5$. With M31 and M33 distance moduli of $(m-M)_0=24.3$ and 24.5, respectively, the red giants in these two Local Group galaxies have $M_I \simeq -3.6$. With $22.5 \lesssim I \lesssim 23.5$ and $M_I \simeq -3.6$ the distance modulus of NGC 253 becomes $26.1 \lesssim (m-M)_0 \lesssim 27.1$, corresponding to $1.7 \lesssim D(\mathrm{Mpc}) \lesssim 2.6$. The observations discussed above are consistent with Graham's conclusion that NGC 253 lies well behind NGC 55 and NGC 300.

NGC 300 is an open-armed low-luminosity spiral galaxy that is eminently suitable for studies of its stellar population. van den Bergh (1963) has classified this object as an Sc III-IV on the DDO system. With an integrated magnitude $B_T=8.7$ and $M_B \simeq -18.0$, which is the mean luminosity of spirals of luminosity class III-IV, one obtains a distance modulus $(m-M)_B \simeq 26.7$, with an estimated uncertainty of 0.7 mag. [The Sc II.8 classification given by Sandage and Tammann (1982) would result in a significantly larger distance.] Intercomparison of the bright end of the luminosity function of planetary nebulae in NGC 300 with those of the planetary nebulae in M31 and the Magellanic Clouds yields $(m-M)_0=25.85 \pm 0.34$ (Lawrie and Graham 1984). However, this determination should be revised by using the ~ 0.4 mag fainter planetary nebula luminosity function cutoff used in recent work and by fitting of the observed luminosity function by maximum likelihood techniques. From a comparison of the I-band luminosities of 16 carbon stars in the LMC [for which $(m-M)_0=18.45$ was adopted], Richer et al. (1985) find $(m-M)_0=25.87 \pm 0.15$ ($D=1.5$ Mpc). The quoted error has been obtained by adding the uncertainties in the mean magnitudes of carbon stars in the LMC and in NGC 300, and the uncertainty in the distance modulus of the Large Cloud, in quadrature.

Photographic observations of red giants in the halo of NGC 300 by Graham (1982) indicate that these objects are ~ 1.3 mag fainter than those in NGC 205. With $(m-M)_V \simeq 24.5$ for NGC 205 it follows that $(m-M)_V \simeq (m-M)_0 \simeq 25.8$ for NGC 300, in excellent agreement with the value obtained for carbon stars. Graham (1984) has published photographic photometry for 18 Cepheids in NGC 300. Using CCD photometry to correct scale errors in Graham's work, Walker (1988b) found a Cepheid modulus $(m-M)_0=26.4 \pm 0.2$. This is in excellent agreement with Freedman et al. (1992) who used CCD photometry of Cepheids in B,V,R, and I to derive a distance modulus $(m-M)_0=26.43 \pm 0.10$ ($D=1.9$ Mpc), for an assumed LMC modulus of 18.45.

By comparing 1.05 μm observations of three Cepheids in NGC 300 with those of Cepheids in Galactic open clusters, Visvanathan (1989) obtains $(m-M)_0=25.72 \pm 0.12$. This value appears to be significantly smaller than those obtained by Walker (1988b) and Freedman et al. (1992).

The determinations of the distance moduli of various members of the Sculptor group given above are summarized in Table 5. On the basis of these data we shall, in the subsequent discussion, adopt $(m-M)_0=25.7 \pm 0.15$ ($D=1.4 \pm 0.1$ Mpc) for NGC 55 and $(m-M)_0=26.0 \pm 0.2$ ($D=1.6 \pm 0.2$ Mpc) for NGC 300.

The Pegasus dwarf galaxy (DDO 216) is located just north of the Sculptor group. From CCD observations of 12 Cepheids, Hoessel et al. (1990) obtain $(m-M)_0=26.08 \pm 0.2$ ($D=1.6$ Mpc) for an LMC modulus of $(m-M)_0=18.45$. With this distance modulus DDO 216 has $M_B \simeq -13.7$.

3.3 The M81 Group

The core of the M81 group consists of NGC 2976, NGC 3031 (M81), NGC 3034 (M82), and IC 2574. The galaxies NGC 2366, NGC 2403, NGC 4236, and UGC 4305 (Ho II) form an extended envelope around this core. The mean angular distance of these objects from M81 is 12°, which, at a distance of 3.2 Mpc, corresponds to ~ 0.7 Mpc. The depth of the cluster along the line of sight is (see Table 4) therefore expected to be ~ 0.9 mag in distance modulus.

Recent distance determinations to M81 and to NGC 2403 are listed in Table 6. The Metcalfe and Shanks (1991) distance moduli $(m-M)_V=27.28 \pm 0.12$ and $(m-M)_B=27.67 \pm 0.14$ were derived from recalibration of old photographic photometry of NGC 2403 by means of CCD observations. Taken at face value these results would indicate that $E(B-V)=0.39 \pm 0.18$. Distance estimates based on the observations of the brightest M-type supergiants by Humphreys et al. (1986) were calibrated by using the observations of M-type supergiants in the Local Group (Humphreys 1983) together with the Local Group distance moduli derived in the present review. This gives $\langle M_V(1)\rangle = -8.2\pm0.1$, with a dispersion of 0.3 mag, in which $M_V(1)$ is the absolute magnitude of the brightest M supergiant. With this calibration the data in Humphreys et al. (1986) yield $(m-M)_0 \leqslant 28.0$ for NGC 2403 and $(m-M)=27.6\pm0.3$ for M81. *Hubble Space Telescope* observations of the Cepheids in M81 will soon provide a good check on this distance estimate. From *I*-band brightness fluctuations in the nuclear bulge of M81 (Tonry 1991), reduced to an M31 distance of 725 kpc (see Sec. 6), one obtains $(m-M)_0=27.62\pm0.15$, corresponding to a distance of 3.3 kpc. In the subsequent discussion a distance modulus of 27.6 ± 0.15 will be adopted for M81.

Photographic photometry of the brightest stars in NGC 2366, NGC 4236, and IC 2366 by Tikhonov et al. (1991) and by Sharina (1991) in NGC 3077 are consistent with $27.4 \leqslant (m-M)_0 \leqslant 27.8$ for these objects.

3.4 The Centaurus Group

A listing of 17 probable members of the Centaurus group is given by Hesser et al. (1984). This group exhibits significant subclustering, with major concentrations surrounding NGC 5128 (Centaurus A) and NGC 5236 (M83). These two objects have radial velocities $v_0=+318\pm30$ km s^{-1} and $v_0=+329\pm10$ km s^{-1}, respectively. (v_0 denotes the heliocentric velocity adjusted for a solar motion of 300 km s^{-1} towards $l=90°$, $b=0°$.) These values are close to the mean group velocity of $\langle v_0\rangle=+314\pm28$ km s^{-1}. The low-luminosity amorphous cluster member NGC 5253 is of particular interest because it has produced the supernovae SN 1895B (type I) and SN 1972E (type Ia) during the last century. Fifteen out of 17 probable group members are situated within $R \leqslant 13\overset{\circ}{.}5$ of NGC 5128. For most group members the range in distance moduli should therefore be $\lesssim 1.0$ mag (see Table 4).

An early distance estimate for the Centaurus group, which was based on diameters of H II regions, was published by Sandage and Tammann (1974b). They obtained distances of 8.1 and 8.9 Mpc for NGC 5068 and NGC 5236, respectively. More recently Hesser et al. (1984) estimated a much smaller distance $\simeq 3$ Mpc from the difference between the luminosities of the brightest globular clusters in NGC 5128 and in the Galaxy. From a comparison of the planetary nebulae in two fields in NGC 5128 with those in M31, Jacoby et al. (1988) find $(m-M)_0=27.87^{+0.09}_{-0.16}$ and $(m-M)_0=27.98^{+0.10}_{-0.16}$. With these values and a correction of 0.10 mag to the Jacoby et al. distance scale (see Sec. 2.1), the distance to NGC 5128 becomes $(m-M)_0=27.8\pm0.1$ ($D=3.6$ Mpc). With this distance Ciardullo et al. (1990) find that the nova rates per unit infrared (*K*-band) luminosity in NGC 5128 and in the nuclear bulge of M31 are identical. Since the nova rate per unit luminosity is $\propto D^{-2}$ this agreement supports the distance estimate given above. From a physical model for SN 1986G, Ruiz-Lapuente et al. (1992) determine a distance of 3.3 ± 0.3 Mpc, corresponding to $(m-M)_0=27.6\pm0.2$. It is of particular interest to note that Ruiz-Lapuente et al. (1992) derive a total mass of $0.38\pm0.03\ M_\odot$ of ^{56}Ni. This

TABLE 7
Distance Moduli of Centaurus Group

Galaxy	Method	Reference	$(m-M)_0$
NGC 5128	Globular clusters	Hesser *et al.* (1984)	~ 27.4
	Planetary nebulae	Jacoby *et al.* (1988)	27.8 ± 0.1
	SN 1986G	Ruiz-Lapuente *et al.* (1992)	27.6 ± 0.2
	Fluctuations	Tonry & Schechter (1990)	27.58
			27.7 ± 0.15
NGC 5236	SN 1968L	Schmidt *et al.* (1992)	28.4 ± 0.4
NGC 5253	HII vel. disp.	Della Valle & Melnick (1992)	28.3 ± 0.3
	Planetary nebulae	Phillips *et al.* (1992)	$27.9^{+0.1}_{-0.5}$
	Fluctuations	Phillips *et al.* (1992)	27.0 ± 0.1

is significantly lower than the value of $0.6\ M_\odot$ of ^{56}Ni which Arnett et al. (1985) used to derive a theoretical luminosity for SN Ia.

Spectroscopic and photometric observations of the type-II supernova 1968L in M83 (Schmidt et al. 1992) yield an unexpectedly large modulus, $(m-M)_0=28.4\pm0.4$. Della Valle and Melnick (1992) also obtain a large distance modulus $(m-M)_0=28.3\pm0.3$, corresponding to 4.6 ± 0.7 Mpc, by application of the velocity dispersion versus Hβ luminosity relation for a large H II region in NGC 5253.

From a statistically complete sample of only ten planetary nebulae, Phillips et al. (1992) derive a distance modulus of $27.9^{+0.1}_{-0.5}$ for NGC 5253. (This modulus has been reduced to the M31 distance found in Sec. 2.2.) From observations of fluctuations by Tonry, Phillips et al. (1992) obtain a discordant distance modulus of 27.0 ± 0.1. Possibly this discrepancy is due to the presence of recently formed bright giant stars in NGC 5253. However, it is puzzling that Tonry's observations close to the nucleus of NGC 5253 (where some star formation is still taking place) yield almost the same distance modulus as do his observations in the outer part of this galaxy.

From *I*-band fluctuation observations of NGC 5128, which has $(V-I)_0=1.07$, Tonry and Schechter (1990) find a fluctuation magnitude $\bar{I}_0=26.08\pm0.06$. With the calibration given in Sec. 6, which is based on a distance of 725 kpc to M31, one then obtains $(m-M)_0=27.58$ corresponding to $D=3.3$ Mpc. Table 7 shows that this value is in excellent agreement with other distance determinations to NGC 5128. In the subsequent discussion it will be assumed that members of the Centaurus group have $(m-M)_0=27.7\pm0.5$. It is hoped that this modulus will, in the not too distant future, be strengthened by multicolor photometry of Cepheids in NGC 5236 and by observations of the maximum magnitude vs. rate-of-decline relation for novae in NGC 5128.

3.5 The M101 Group

The M101 (=NGC 5457) group was first discussed by Holmberg (1950), who included M51 (=NGC 5194) as a group member. A more restrictive membership, including only M101 itself, NGC 5204, NGC 5477, NGC 5585, and Holmberg IV was adopted by Sandage and Tammann (1974b). All of these objects are situated within 8° of

M101, so that one expects $\Delta(m-M)_0 \lesssim 0.6$ mag for group members. Unfortunately M101 is viewed almost pole-on so that this exceptionally large Sc I galaxy is not suitable for calibration of the Tully–Fisher relation.

Two Cepheids were discovered in M101 by Cook et al. (1986). Detailed R-band photometry of these Cepheids (Illingworth 1992), which have periods of 47 days and 37 days, yields $\Delta(m-M)_R = 10.8$ for the difference in the distance moduli of M101 and the LMC. With a Large Cloud modulus of $(m-M)_0 = 18.45$ and $A_R(\mathrm{LMC}) \simeq 0.2$, one then has an M101 modulus $(m-M)_R \simeq 18.65 + 10.8 = 29.45$, and hence $(m-M)_0 \simeq 29.45 - A_R$, in which A_R is the mean absorption suffered by the Cepheids in M101.

From spectroscopic and photometric observations of the Type-II supernova 1970G, Schmidt et al. (1992) find $(m-M)_0 = 29.4 \pm 0.5$, which is in good agreement with the Cepheid distance modulus.

Observations of the M-type supergiants in the Local Group, together with the distance moduli given in Sec. 2, yields $M_V(1) = -8.2 \pm 0.1$ for the brightest M supergiant in late-type spiral galaxies. From V- and K-band photometry, Humphreys et al. (1986) find $V_0(1) = 20.2$ for the two most luminous supergiants in M101, so that $(m-M)_0 = 28.4$. This value is one magnitude smaller than the apparent red distance modulus obtained from Cepheids. This indicates that either (1) the brightest supergiant stars in M101 are significantly brighter than they are in the less-luminous Local Group galaxies, or (2) $A_R \simeq 1.0$ mag for the two Cepheids for which Illingworth (1992) has obtained photometry. Multicolor CCD photometry of Cepheids in M101 is needed to clarify this point.

3.6 The M66 and M96 Groups

The M96 (NGC 3368) group at $\alpha = 10^{\mathrm{h}}46^{\mathrm{m}}9$, $\delta = +12°33'$ (equinox 2000) and the M66 (NGC 3627) group at $\alpha = 11^{\mathrm{h}}15^{\mathrm{m}}0$, $\delta = 13°17'$ are separated by only 6°9 and have mean velocities of $\langle v_0 \rangle = +681 \pm 33$ km s^{-1} and $\langle v_0 \rangle = +627 \pm 40$ km s^{-1}, respectively. It seems highly probable that these two groups are physically associated and that they are situated at approximately the same distance. According to de Vaucouleurs (1975), the principal members of these groups, in order of decreasing luminosity, are NGC 3368 (=M96), NGC 3351, NGC 3379, NGC 3384, NGC 3377, and NGC 3627 (=M66), NGC 3628, NGC 3623, NGC 3489, NGC 3593.

Ciardullo et al. (1989) have observed 93 planetary nebulae in NGC 3379, 54 in NGC 3377, and 102 in NGC 3384. Using the forground absorption values of Bustein and Heiles (1984), and after applying a 0.10 mag correction to bring the M31 distance modulus into accord with the one derived in Sec. 2.1, one obtains $(m-M)_0 = 29.97$ for NGC 3377, $(m-M)_0 = 29.86$ for NGC 3379, and $(m-M)_0 = 29.93$ for NGC 3384.

Harris (1990) finds that the peak of the luminosity function of the globular clusters in NGC 3377 and NGC 3379 occurs at $B_0 = 23.35 \pm 0.40$. Equating this to the absolute magnitude of the peak of the Galactic globular-cluster luminosity function at $M_B^0 = -6.7 \pm 0.15$ yields $(m-M)_0 = 30.05 \pm 0.43$ for the distance modulus of the M96 Group.

TABLE 8
Distance Moduli of M66/M96 Group Galaxies

Galaxy	Method	Reference	$(m-M)_0$
NGC 3377	Planetary nebulae	Ciardullo *et al.* (1989)	29.97
	Fluctuations	Tonry(1991)	29.72 ± 0.05
NGC 3377/79	Globular clusters	Harris(1990)	30.05 ± 0.43
NGC 3379	Planetary nebulae	Ciardullo *et al.* (1989)	29.86
	Fluctuations	Tonry *et al.* (1989)	29.7
NGC 3384	Planetary nebulae	Ciardullo *et al.* (1989)	29.93
			29.87 ± 0.05
NGC 3627	SN 1973R	Schmidt *et al.* (1992)	29.4 ± 0.5
NGC 3368, 3623, 3627, 3628	Tully-Fisher	Bottinelli *et al.* (1983, 1985)	29.87 ± 0.35

The surface-brightness fluctuations in M32 and in NGC 3379 have been compared by Tonry and Schneider (1988) and Tonry et al. (1989). Assuming that M31 and M32 both have the same distance modulus of $(m-M)_0 = 24.3$ yields (after correcting for a difference in metallicity between M32 and NGC 3379) $(m-M)_0 = 29.7$. A distance modulus (see Sec. 6) of 29.72 ± 0.05 is derived from Tonry's (1991) observations of surface-brightness fluctuations in NGC 3377.

Bottinelli et al. (1985) have used the Tully–Fisher relation to derive a mean distance modulus of 29.70 ± 0.20 for NGC 3368, NGC 3623, NGC 3627, and NGC 3628. For four standards in common between Bottinelli et al. and the present review (M31, M33, M81, and NGC 300) $\langle \Delta(m-M)_0 \rangle = 0.17 \pm 0.29$, so that $(m-M)_0 = 29.87 \pm 0.35$ for the M66 and M96 groups.

From spectroscopic and photometric observations of the Type-II supernova 1973R, in NGC 3627, Schmidt et al. (1992) find $(m-M)_0 = 29.4 \pm 0.5$.

The distance determinations to the M96 group are summarized in Table 8. The agreement between these quite distinct methods of distance determinations is seen to be excellent. The fact that different methods of distance determination give concordant results out to a distance of almost 10 Mpc greatly strengthens confidence in the reliability of presently available techniques for distance determinations. In the subsequent discussion it will be assumed that this group has $(m-M)_0 = 29.9 \pm 0.1$.

3.7 The NGC 1023 Group

According to de Vaucouleurs (1975) the members of this group, for which $\langle v_0 \rangle = +792 \pm 59$ km s^{-1}, are (in order of decreasing luminosity) NGC 1023, NGC 891, NGC 925, IC 239, NGC 1058, and NGC 1003. The galaxies in this group extend up to a distance of 6° from NGC 1023. The depth of the group along the line of sight (see Table 4) is therefore expected to be $\Delta(m-M)_0 \simeq 0.5$ mag.

The planetary nebulae in NGC 891 and in NGC 1023 have been studied by Ciardullo et al. (1991). From 110 planetaries in NGC 1023 these authors find $(m-M)_0 = 29.87 \pm 0.14$. An identical modulus of $(m-M)_0 = 29.87$

± 0.16 is obtained from 33 planetary nebulae in NGC 891. (Both of these values are referred to the distance modulus and reddening of M31 adopted in Sec. 2.1.)

Aaronson and Mould (1983) have obtained H-band photometry and 21 cm linewidths for five galaxies in the NGC 1023 group. After correcting the zero point of their Tully–Fisher relation by -0.13 ± 0.06 mag, to bring it into agreement with the M31, M33, and M81 distances used in the present review, one obtains a group distance modulus $(m-M)_0 = 29.85 \pm 0.25$. This value is seen to be in excellent agreement with that derived from planetary nebulae.

From spectrographic and photometric observations of the Type-II supernova 1969L in NGC 1058, Schmidt et al. (1992) find $(m-M)_0 = 30.25 \pm 0.3$.

A value $(m-M)_0 = 29.9 \pm 0.2$ ($D = 9.5$ Mpc) for the distance to the NGC 1023 group will be adopted in the subsequent discussion.

4. LUMINOSITY CALIBRATION OF SN Ia

The Lupus supernova of 1006 and Tycho's supernova of 1572 are widely believed to have been of Type Ia. However, neither their distances, nor their apparent magnitudes and colors at maximum light, are known well enough to allow them to be used to calibrate the luminosity of SN Ia. According to de Vaucouleurs and Corwin (1985) the spectrum of SN 1885 (=S And) did *not* exhibit the λ 6150 Å absorption feature that is diagnostic of SN Ia, so that it cannot be used as a calibrator either.

The nearest supernovae of Type Ia that can be used as calibrators are SN 1972E and SN 1986G. The heavily reddened supernova 1986G occurred in the dust band that crosses the face of NGC 5128. According to Phillips et al. (1987), this object had $B(\max) = 12.45 \pm 0.05$ and $(B-V)_{\max} = 1.03$. Adopting $(B-V)_0^{\max} = 0.00$ (van den Bergh and Pierce 1992) and $A_B = 4.3\,E(B-V)$, this yields $A_B = 4.43$ mag. Because of the nonstandard color evolution of SN 1986G, its intrinsic color at maximum, and hence its reddening, are quite uncertain. With $B(\max) = 12.45$ and $A_B = 4.43$, one obtains $B_0(\max) = 8.02$. Adopting a distance modulus $(m-M)_0 = 27.7 \pm 0.15$ yields $M_B(\max) = -19.7 \pm 0.15$, in which the quoted error does *not* take into account the uncertainty in the absorption that results from the possibly anomalous colors of this object. (Nor does it take into account the ~ 0.1 mag uncertainty in the intrinsic colors of SN Ia at maximum light.)

The light curve of SN 1972E in NGC 5253 is not well determined at maximum light. By combining all published observations, Leibundgut et al. (1991) estimate $B(\max) = 8.45$, which, with a foreground absorption $A_B = 0.19$ (Burstein and Heiles 1984), gives $B_0(\max) = 8.26$. (In arriving at this value it was assumed that internal absorption in the amorphous galaxy NGC 5253, at the position of SN 1972E, can be neglected.) With $B_0(\max) = 8.26$ and $(m-M)_0 = 27.7 \pm 0.5$, one obtains $M_B(\max) = -19.44 \pm 0.5$. It is of interest to note that $B_0(\max) = 8.26$ for SN 1972E is close to the value $B_0(\max) = 8.02$ previously found for SN 1986G, which was also located in the Centaurus group.

Pierce et al. (1992) have used CCD observations of the brightest red supergiants in IC 4182, which produced the Type Ia supernova 1937C, to derive a distance modulus of $(m-M)_0 = 27.0$ with a (possibly optimistic) error of $\pm$ 0.2 mag. Combining this value with $m_{pg}(\max) = 8.5 \pm 0.2$ (Leibundgut et al. 1991), corresponding to $B(\max) = 8.8 \pm 0.2$, and assuming no foreground absorption (Burstein and Heiles 1984) and zero internal absorption in the dwarf galaxy IC 4182, one obtains $M_B(\max) = -18.2$ for SN 1937C. A significantly higher luminosity of SN 1937C would, however, be derived from the distance modulus derived via *photographic* photometry of red giants in IC 4182 by Sandage and Tammann (1982).

Hamuy et al. (1991) have obtained photoelectric observations of two supernovae of Type Ia in NGC 1316 in the Fornax cluster. They find $B(\max) = 12.49$ for SN 1980N and $B(\max) = 12.59$ for SN 1981D. Adopting the distance modulus $(m-M)_B \simeq (m-M)_0 = 30.64 \pm 0.07$, which is derived from Tonry's (1991) fluctuations method, yields $M_B(\max) = -18.15$ and $M_B(\max) = -18.05$ for SN 1980N and SN 1981D, respectively. These values are close to that which Pierce et al. (1992) derive for SN 1937C in IC 4182, but are much fainter than those obtained above for SN 1986G in NGC 5128 and for SN 1972E in NGC 5253. A more detailed discussion of the suitability of SN Ia as distance calibrators will be given in Sec. 8.1

5. GLOBULAR CLUSTERS AS DISTANCE INDICATORS

Globular clusters are potentially useful as standard candles because they are luminous and often occur well outside the main bodies of their parent galaxies.

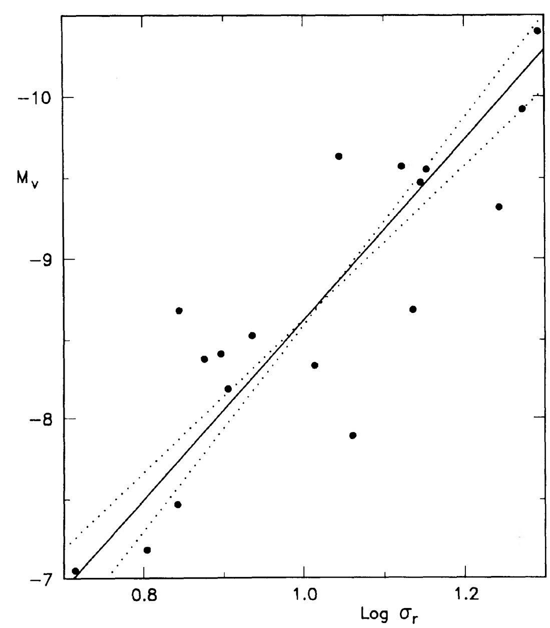

FIG. 2—Velocity dispersion vs absolute magnitude of Galactic globular clusters. Dotted lines are regressions of M_V on log σ_r and of log σ_r on M_V. The adopted (thick) line has slope $b = 5.53$ and passes through $\langle M_V \rangle = -8.69$ and $\langle \log \sigma_r \rangle = 1.017$.

TABLE 9
Radial Velocity Dispersions of M31 Clusters

Bo.no.	Name	L[a]	V[a]	(B-V)[a]	E(B-V)[b]	V_o	log σ_r	$(m-M)_o$
19	44	7	14.98	0.96	0.23	14.22	1.279	24.36
20	M III	3	15.78	0.70	0.07	15.55	1.255	25.56
147	91	8	15.29	0.93	0.18	14.70	1.041	23.52
163	100	13:	15.03	1.03	0.18	14.44	1.322	24.82
171	87	14	15.20	0.98	0.11	14.84	1.255	24.85
193	116	12	15.20	0.99	0.16	14.81	1.079	23.84

[a] From van den Bergh (1969)

[b] Includes foreground reddening of E_{B-V} = 0.07.

TABLE 10
Radial Dependence of Galactic Globular-Cluster Luminosities

log R(pc)	$< M_V >$	σ(mag)	n
<3.5	-6.94 ± 0.21	1.28	38
3.6	-7.30 ± 0.27	1.21	20
3.8	-7.34 ± 0.24	1.21	26
4.0	-7.49 ± 0.35	1.57	20
4.2	-7.09 ± 0.35	1.53	19
>4.3	-6.19 ± 0.38	1.88	25

5.1 Velocity Dispersions in Globulars

Recently Paturel and Garnier (1992) have shown that the radial-velocity dispersions σ_r in globular clusters correlate rather well with their absolute magnitudes M_V. Using their listing of velocity dispersions, together with the cluster absolute magnitudes of Webbink (1985) [which are based on $M_V(\mathrm{RR})=+0.6$], one finds a correlation coefficient $r=0.86\pm0.06$ between σ_r and M_V of Galactic globular clusters. The dispersion of individual clusters about the relation

$$M_V=-8.69-5.53(\log\sigma_r-1.017), \qquad (1)$$

which is plotted in Fig. 2, is 0.5 mag. It should be noted that 15 out of 18 clusters plotted in this diagram are core-collapsed clusters of profile-type C (van den Bergh et al. 1991). It is not yet possible to say if deviations from Eq. (1) correlate with cluster profile type.

Table 9 contains data on six M31 globular clusters from van den Bergh (1969), together with the radial-velocity dispersions quoted in Paturel and Garnier (1992). Using these data, in combination with Eq. (1), yields $(m-M)_0=24.5\pm0.3$ for the Andromeda nebula. This value is in good agreement with $(m-M)_0=24.3\pm0.1$ derived by van den Bergh (1989) from all other modern distance determinations to M31.

Because of its relatively small scatter, the M_V-versus-σ_r relation appears to provide a powerful tool for the determination of distances to galaxies that are surrounded by globular-cluster systems. Once the new generation of 8-m class telescopes becomes available, it might become possible to compare the apparent magnitudes and internal-velocity dispersions of globular clusters in M31 and in the Virgo cluster to determine the Virgo distance modulus.

5.2 Globular Clusters as Standard Candles

In a recent review Harris (1991) shows that the absolute magnitude M_V^0 of the peak of the globular-cluster luminosity function appears to differ little, or not at all, over a range of $\sim10^4$ in parent-galaxy luminosity. Perhaps even more remarkable is the fact that there appears to be no systematic difference between the M_V^0 values of globular clusters in spiral and elliptical galaxies. This suggests that the integrated magnitudes of globular clusters might be useful standard candles for calibration of the extragalactic distance scale.

The radial dependence of $\langle M_V\rangle$ for Galactic globular clusters may be used to probe the sensitivity of cluster luminosities (and masses) to environmental factors. Table 10, which is based on the compilation of globular-cluster data by Webbink (1985), shows no convincing radial trend in the luminosities of Galactic globular clusters, except for a luminosity decrease in the outermost bin due to the presence of "Palomar-type" clusters. There does, however, appear to be a real radial increase in the luminosity dispersion of Galactic globular clusters.

From observations of 75 halo globular clusters by Harris et al. (1991), Racine and Harris (1992) find that $M_V^0=-7.29\pm0.13$, with $\sigma=1.4$ mag. This M_V^0 value was obtained by assuming $M_V(\mathrm{RR})=0.2$ [Fe/H]$+1.0$, which gives $M_V(\mathrm{RR})=+0.7$ for a mean halo metallicity $\langle$[Fe/H]$\rangle=-1.5$. Adopting instead the value $M_V(\mathrm{RR})=+0.6$, which is used throughout the present review, yields $M_V^0=-7.39\pm0.13$ for Galactic globular clusters.

For 82 globular clusters in the halo of M31 that were observed by Reed et al. (1992), Racine and Harris (1992) find $V^0=17.00\pm0.18$ with $\sigma=1.1$ mag for the cluster luminosity function. (This value of the dispersion is somewhat uncertain because of incompleteness of the data at faint magnitudes.) With $(m-M)_0=24.3\pm0.1$, $E(B-V)=0.07$ and $A_V/E(B-V)=3.3$, this yields $M_V^0=-7.53\pm0.21$ for the globulars in M31. Within its statistical uncertainty this value is indistinguishable from the value $M_V^0=-7.39\pm0.13$ previously found for globular clusters in the Galactic halo. The data for globular clusters in the halos of the Galaxy and M31 therefore support the notion that the luminosity functions of globular clusters are very similar in different luminous spirals. In the subsequent discussion it will be assumed that $M_V^0=-7.4\pm0.15$ and $M_B^0=-6.7\pm0.15$ for all globular-cluster systems.

Harris et al. (1991) have observed the luminosity functions of the globular-cluster systems surrounding three giant elliptical galaxies in the Virgo cluster. Their data extend to well below the peaks of the cluster luminosity functions. The luminosity functions of these three globular-cluster systems, and that of M87, peak at $B^0=24.77$, with a galaxy-to-galaxy scatter of about ±0.2 mag. The luminosity functions of all these cluster systems, are well represented by a Gaussian with $\sigma=1.46\pm0.07$ mag. The *assumption* that the luminosity function in M_V of the globulars in the Galactic halo is identical to that of the globular clusters associated with the giant elliptical galaxies in the Virgo cluster yields a Virgo distance modulus $(m-M)_0=(m-M)_B=24.77+6.7=31.47\pm0.25$. Note, however, that this quoted error does not include the uncertainty introduced by the assumption that the luminosity functions of globular-cluster systems in giant spiral and ellipticals are identical. A useful check on this hypothesis might be provided by observations of elliptical and edge-on spiral galaxies in the Coma I group.

Bridges and Hanes (1992) have recently observed the luminosity function of the globular clusters associated with the Sombrero galaxy (NGC 4594=M104). Assuming a Gaussian luminosity function with $\sigma=1.5$ mag, these authors obtain $B^0=24.1\pm0.3$, which, with $A_B=0.1$ mag, yields $B_0^0=24.0\pm0.3$, and hence $(m-M)_0=24.0+6.7=30.7$ This indicates that the Sombrero galaxy lies slightly in front of the Virgo cluster. Alternatively, it might also be assumed that the globular clusters in M104 are more luminous than those surrounding Virgo cluster galaxies.

The globular-cluster system associated with NGC 1399, which is the central galaxy in the Fornax cluster, has been studied by Geisler and Forte (1990), Wagner et al. (1991), and Bridges et al. (1991). The last-named authors find that the NGC 1399 cluster luminosity function peaks at $B^0=24.6\pm0.52$ (estimated uncertainty). A peak magnitude that is 0.35 mag brighter than this was previously found by Geisler and Forte (1990). Both of these results are, however, quite uncertain because the cluster counts only barely extend beyond the peak of the cluster luminosity function. With $B^0=24.6\pm0.5$, $M_B^0=-6.7\pm0.15$, and $A_B=0.0$ (Burstein and Heiles 1984), one obtains a Fornax cluster distance modulus of $(m-M)_0=31.3\pm0.5$.

Very recently Richtler et al. (1992) have found that the luminosity function of the globular clusters in the Fornax cluster galaxy NGC 1404 peaks at $V^0=24.1\pm0.2$, which differs only marginally from the value $V^0\sim23.8$ for the peak of the luminosity function of NGC 1399 (Bridges et al. 1991), which is the central galaxy of the Fornax cluster.

6. SURFACE-BRIGHTNESS FLUCTUATIONS

Distant globular clusters, elliptical galaxies, and the bulges of spirals exhibit incipient resolution. Tonry and Schneider (1988) showed that the resulting surface-brightness fluctuations can, when properly calibrated, be used to determine the distances to early-type systems. A detailed discussion of this technique is given in Jacoby et al. (1992). Studies of individual galaxies using surface-brightness fluctuations are quoted in Tonry et al. (1988), Tonry et al. (1989, 1990), and Tonry and Schechter (1990). Surface-brightness variations in the I band are particularly useful for distance determinations because late-type giant stars are brighter in I than they are in B, V, and R, and because dust absorption is lower in I than it is at shorter wavelengths. The most recent study of surface-brightness fluctuations in the I band is by Tonry (1991). In that investigation Tonry used a distance of 770 kpc to M31, compared to a distance of 725 kpc adopted throughout the present review. With this revised distance the calibration for infrared fluctuation magnitudes $\bar{M}_I$ becomes

$$\bar{M}_I=-4.71+3.0(V-I)_0\,, \qquad (2)$$

where $(V-I)$ is the integrated color index of the galaxy in which fluctuations are being observed. The surface-brightness fluctuation technique has been used to determine distances to the M81, Centaurus, and Leo groups, and to the Virgo, Fornax, and most recently (Tonry 1991) the Eridanus clusters.

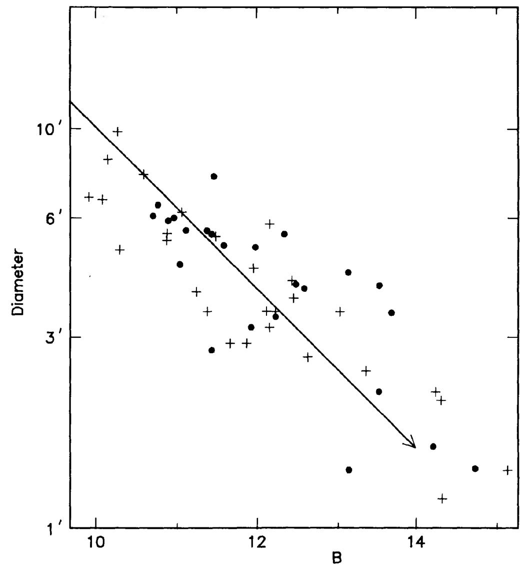

FIG. 3—Relation between angular diameter and apparent magnitude for galaxies in the Virgo (+) and Ursa Major (●) clusters. The arrow shows a distance-degenerate line.

7. GALAXY DIAMETERS AS YARDSTICKS

Figure 3 shows a plot of galaxy diameter (Nilson 1973) versus B magnitude (Pierce and Tully 1988) for spiral galaxies in the Virgo and Ursa Major clusters. The figure shows that luminous spirals in these two, roughly equidistant, clusters exhibit a distance-degenerate relation of the form

$$\log\phi=A-0.2B, \qquad (3)$$

in which ϕ is the angular diameter of the major axis and B is the apparent blue magnitude. Note, however, that intrinsically faint galaxies fall slightly above this distance-degenerate line, i.e., they have lower surface brightnesses than do giant and supergiant galaxies.

7.1 Diameters of Sc I Galaxies

Recently Sandage (1992) has used a comparison between the diameter of the field Sc I spiral M101 and the diameter of M100, which is the largest spiral in the Virgo cluster, to obtain a Hubble parameter $H_0=43\pm11$ km s^{-1} Mpc^{-1}. Such a comparison is only meaningful if the diameters of Sc I galaxies exhibit little intrinsic dispersion. That this assumption is unwarranted is demonstrated by

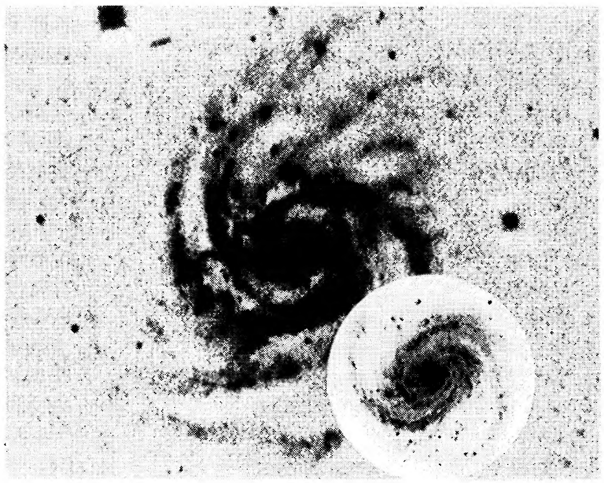

FIG. 4—Kitt Peak 4-m plates of the Sc I galaxies NGC 309 in Cetus and M100 in the Virgo cluster printed to the same linear scale.

Fig. 4, which shows that the Sc I galaxy NGC 309 is much larger than M100, which is also of type Sc I. The reason that Sandage (1992) obtains such a small value for H_0 is that M101 happens to be an unusually large Sc I galaxy. From an intercomparison of the catalogs of Tully (1988) and Sandage and Tammann (1981), it is found that the nearest other Sc I galaxy which is as large (or larger) than M101 is NGC 1232. This object has a redshift $v_0=1607$ km s^{-1}, which, for $H_0=75$ km s^{-1} Mpc, places it at a distance of 20 Mpc. Clearly M101 is an unusually large Sc I. Comparing it with the more nearly normal spiral M100 will therefore give a Virgo cluster distance that is substantially too large, and hence an H_0 value that is too small.

7.2 Luminosity Classifications and Galaxy Diameters

The most luminous Sc I galaxies tend to have the largest diameters. Objects at the extreme tail of the luminosity distribution of Sc I galaxies, such as NGC 309, can therefore have very large diameters. However, the range of luminosities (and hence of diameters) becomes somewhat more restricted for galaxies with lower luminosities such as M31 (Sb I-II), M33 (Sc II-III), and the LMC (Ir III-IV). It is therefore possible to obtain a rough distance estimate of the presumably equidistant (see Sec. 9.1) Virgo and Ursa Major clusters by comparing the linear diameters of M31, M33, and the LMC with the angular diameters [corrected for inclination and obscuration (Tully 1988)] of intermediate and late-type galaxies with similar luminosity classes (van den Bergh et al. 1990) in the Virgo and Ursa Major clusters. From such a comparison, and distances of 50, 725, and 795 kpc for the LMC, M31, and M33, respectively, one obtains the following distances for the Virgo/Ursa Major clusters: From M31 $17.1^{+3.1}_{-2.3}$ Mpc, from M33 $10.6^{+3.2}_{-2.0}$ Mpc, and from the Large Cloud $12.2^{+3.5}_{-2.2}$ Mpc, in which the quoted uncertainties are *estimated* mean errors. The corresponding Virgo distance moduli are 31.15 ± 0.35, 30.1 ± 0.5, and 30.4 ± 0.5, respectively. These distance moduli are, of course, based on the assumption that there are no systematic differences between the diameters of galaxies in low-density aggregates such as the Local Group, and denser cluster such as Ursa Major and Virgo.

7.3 Diameters of Dwarf Ellipticals

Bothun et al. (1989) find that the scale lengths of the surface-brightness distributions for dwarf elliptical galaxies exhibits a range of only about a factor of 2. Furthermore, these authors find no dependence of the scale length of dwarf ellipticals on their luminosity. [A similar situation prevails in Galactic globulars in which r_h, the radius containing half of the cluster light (van den Bergh et al. 1991) is independent of cluster luminosity.] From a comparison between the distribution of the angular scale lengths in the Fornax and Virgo clusters, Bothun et al. find D(Fornax)/D(Virgo)$=0.93\pm0.06$. It would clearly be very desirable to obtain more observations to place the conclusion that the diameters of dE galaxies have a small dispersion, and do not depend on luminosity, on a firmer footing. In a generalization of the work of Bothun et al. (1989), Capaccioli et al. (1992) find that *all* ellipticals, except those formed by mergers, have effective radii $R_e \lesssim 2.1$ h^{-1} kpc.

8. SUPERNOVAE

Supernovae are among the most luminous objects in the Universe. If they are standard candles they would therefore be extremely powerful calibrators of the extragalactic distance scale.

8.1 Supernovae of Type Ia

Standard candles have to be identical. In recent years it has become increasingly clear (van den Bergh 1993) that there are real differences between individual supernovae of Type Ia. Branch et al. (1988) have shown that SN Ia exhibit a wide range of expansion velocities. Some of them, such as SN 1986G (Frogel et al. 1987; Phillips et al. 1987), show deviant color evolution. Very recently SN 1991T (Phillips et al. 1992) and SN 1991bg (Filippenko et al. 1992) have demonstrated that some SN Ia exhibit very peculiar spectra at maximum light. Finally SN 1991bg was clearly subluminous at maximum. It is not yet clear if it might eventually be possible to isolate spectroscopically a subsample of SN Ia that are, indeed, identical standard candles.

8.2 Supernovae of Type II

Supernovae of Type II exhibit a range of at least a factor of 10^2 in their luminosities at maximum light. As a result they cannot be used as standard candles. However, it is possible to calculate the luminosities of individual objects for which detailed photometry and spectroscopy is available. The most recent investigation of SN II using the expanding photosphere (Baade-Wesselink) method is by Schmidt et al. (1992). These authors use non-LTE photospheric models, observations of SN 1987A in the LMC, and models for the explosions of massive stars to obtain distances to individual supernovae of Type II. In Table 11

TABLE 11
Distances to Supernovae

Object	Supernova	$(m-M)_0^a$	$(m-M)_0^b$	cluster/group
NGC 5236	1968L	28.4 ± 0.4	27.7 ± 0.5	(Centaurus group)
M 101	1970G	29.4 ± 0.5	≤29.45	M 101 group
NGC 3627	1973R	29.4 ± 0.5	29.85 ± 0.3	M 66/M 96 group
NGC 1058	1969L	30.25 ± 0.3	29.9 ± 0.4	NGC 1023 group
M100	1979C	31.4 ± 0.6	31.0 ± 0.15	Virgo cluster
NGC 4579	1988A	31.8 ± 0.4	31.0 ± 0.15	Virgo cluster

[a] From Schmidt, Kirshner & Eastman (1992)

[b] Distances obtained by conventional techniques

these distances are compared with those obtained by other techniques. Inspection of the data in this table shows that a supernova distance and the distance of its parent galaxy, cluster, or group generally agree within their quoted mean errors. However, in four out of five cases the supernova distance is larger than that derived by means of other techniques. It is not yet clear if this indicates that there is a real systematic difference between distances derived using the expanding photosphere technique and distances derived by other means.

9. DYNAMICAL DISTANCE DETERMINATIONS

Oepik (1922) was the first to use a dynamical method to estimate the distance to a galaxy. His distance of 450 kpc for M31 is now known to have been more accurate than Hubble's (1929) distance of 275 kpc that was derived from observations of Cepheids in the Andromeda nebula. Recent developments in this field build on the study of Faber and Jackson (1976) regarding the correlation between the luminosity and velocity dispersion in ellipticals, and on the relation between the luminosity and rotational velocity of spirals, which was first discussed by Tully and Fisher (1977).

9.1 The Tully–Fisher Relation

An excellent review of previous work on the Tully–Fisher (TF) relation is given in Jacoby et al. (1992). The slope, zero point, and dispersion in the H-band TF relation has been studied by Freedman (1990). Furthermore, Fukugita et al. (1991) have discussed the slope and zero point of the B-band TF relation. Finally Pierce and Tully (1992) derive the slope, zero point, and dispersion of the TF relation in B, R, I, and H.

Both Freedman (1990) and Pierce and Tully (1992) find that the intrinsic dispersion in the Tully–Fisher relation is quite small. It follows that the best strategy is to calibrate the TF relation using only those galaxies with the most accurately determined distances. A comparison between the true distance moduli μ used by Pierce and Tully (1991) and the $(m-M)_0$ values adopted in the present paper is shown in Table 12. The data in this table can be used to determine corrections to the zero points of the magnitude-versus-linewidth relations adopted by Pierce and Tully. Note that the slopes of their relations were, in the first instance, determined from the Ursa Major cluster, so that they will not be significantly affected by the new distance moduli of individual calibrators used in the present investigation.

From the data in Table 12 it is found that the absolute magnitudes predicted by the luminosity–linewidth relations given by Tully and Fisher (1992) are too bright by the following (barely significant) amounts:

$$\Delta M_B=0.12\pm0.19 \text{ mag } (\sigma_B=0.46 \text{ mag}),$$

$$\Delta M_R=0.13\pm0.15 \text{ mag } (\sigma_R=0.37 \text{ mag}),$$

$$\Delta M_I=0.14\pm0.13 \text{ mag } (\sigma_I=0.32 \text{ mag}),$$

and

$$\Delta M_H=0.21\pm0.16 \text{ mag } (\sigma_H=0.32 \text{ mag}).$$

Reducing the distance moduli given by Pierce and Tully (1988) by 0.15 mag yields a Virgo distance modulus $(m-M)_0=30.88$, and an Ursa Major distance modulus $(m-M)_0=30.80$. The uncertainty of these values is estimated to be ±0.2 mag. The assumption that the internal absorption in the edge-on dwarf NGC 3109 is, in fact, zero would increase the systematic correction to the distance moduli of Pierce and Tully to 0.19 mag and increase the dispersion of the absolute magnitudes of local calibrators around the adopted regression lines by 1/3 in B while leaving the dispersion in I unchanged.

Jacoby et al. (1992) find that systematic differences often occur between distances of clusters derived from the

TABLE 12
Adopted Input Parameters for the Tully–Fisher Relation

Galaxy	A^i_B	A^b_B	Log W^i_R	$M_B^{b,i}$	$M_R^{b,i}$	$M_I^{b,i}$	$M_H^{b,i}$	μ	$(m-M)_0$
NGC 224	0.61	0.30	2.712	-20.82	-21.94	-22.52	-23.45	24.3	24.3 ± 0.1
NGC 598	0.16	0.30	2.322	-18.65	-19.35	-19.72	-20.66	24.5	24.5 ± 0.2
NGC 3109	0.67	0.13	2.032	-15.63	-16.24	-16.52	...	25.9	25.4 ± 0.2
NGC 55	0.67	0.05	2.224	-17.94	-18.52	-18.82	...	26.5	25.7 ± 0.15
NGC 300	0.09	0.05	2.284	-17.76	-18.32	-18.70	-19.01	26.5	26.0 ± 0.2
NGC 3031	0.19	0.17	2.685	-20.24	-21.49	-22.06	-23.25	27.7	27.6 ± 0.15

[a] All symbols have the same definitions as in Pierce & Tully (1992).

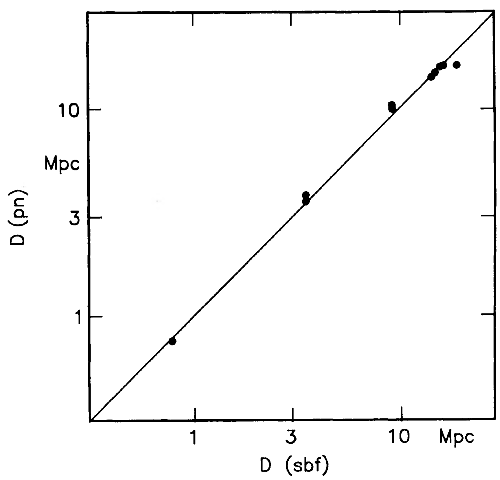

FIG. 5—Comparison between distances derived from the luminosity functions of planetary nebulae and surface-brightness fluctuations (Tonry 1991).

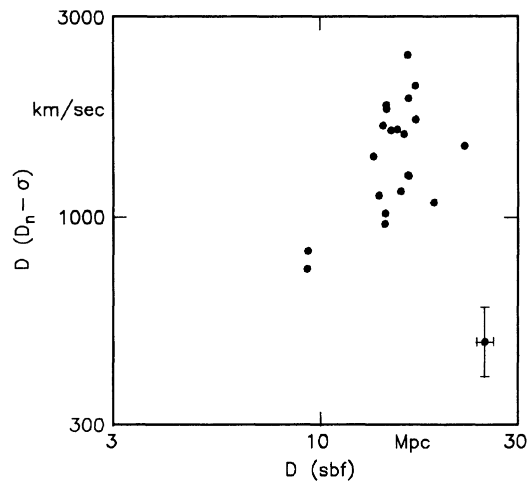

FIG. 6—Comparison between D_n-σ and distances derived from surface-brightness fluctuations. Intercomparison of Figs. 5 and 6 suggests that distances derived from D_n-σ have a larger dispersion than do those obtained from the luminosity functions of planetaries and from surface-brightness fluctuations.

Tully–Fisher relation applied to spirals and cluster distances derived from ellipticals. They argue that this effect is due to the fact that clouds of spirals are often distributed asymmetrically around the early-type galaxies that populate the cores of rich clusters. The effects of Malmquist bias on distances derived from the Tully–Fisher relation have recently been discussed by Fukugita et al. (1991) and by Landy and Szalay (1992).

9.2 The Faber–Jackson Relation

The relation between the luminosity and velocity dispersion of elliptical galaxies was first explored by Faber and Jackson (1976). More detailed work by Tonry and Davis (1981) and by Terlevich et al. (1981) subsequently showed that the luminosity of ellipticals is actually determined by both their velocity dispersion *and* surface brightness. An extensive compilation of redshifts predicted from the D_n-σ relation (in which D_n is the diameter that encloses a mean blue surface brightness of 20.75 mag arcsec^{-2}) is given in Faber et al. (1989).

Tonry (1991) shows that the correlation of distances of elliptical galaxies derived from the D_n-σ relation with those obtained from surface-brightness fluctuations exhibits a much larger dispersion than does that between distances derived from the luminosity functions of planetary nebulae and surface-brightness fluctuations (see Figs. 5 and 6). The distance of a single galaxy derived from the D_n-σ relation is uncertain by 23%. This indicates that distances derived from the D_n-σ relation are probably more useful in a statistical sense than they are individually. A very detailed discussion of the D_n-σ relation and its limitations is given in Jacoby et al. (1992). Gregg (1992) argues that ellipticals which have undergone star-forming events in their recent past will have above-average surface brightnesses. Furthermore, D_n may be affected by mergers. Lucey et al. (1991) find that the ellipticals in the Virgo and Coma clusters lie on intrinsically different fundamental planes. However, recent work by Lucey et al. (1991) has cast some doubt on this conclusion. Finally, de Carvalho and Djorgovski (1992) find systematic differences between field and cluster ellipticals. These authors conclude that, as a consequence of these systematic differences, field ellipticals do not follow the same distance indicator relations as do ellipticals in rich clusters. In very distant clusters poor seeing can cause diameters to be underestimated, resulting in an overestimate of their distances. In view of these potential problems, considerable caution should be exercised in using the D_n-σ relation for ellipticals in efforts to determine the Hubble parameter.

10. DISTANCE TO THE VIRGO CLUSTER

Shapley and Ames (1932) first showed that the Virgo cluster forms the core of the Local Supercluster. Early work by de Vaucouleurs (1961) demonstrated that the Virgo region has a complex structure and that there are at least two overlapping clusters or clouds of galaxies with differing galaxian population content, and at different distances, in this direction. Subsequently this conclusion was strongly supported by the work of Pierce and Tully (1988), who showed that the dispersion in the apparent magnitude-versus-linewidth relation of Virgo cluster galaxies is, because of the cluster depth along the line of sight, much greater than it is in the Ursa Major cluster. The conclusion that the structure of the Virgo region is complex was also supported by van den Bergh (1989) who showed that the integrated H I flux for a complete sample of spiral galaxies in the direction of Virgo exhibits a distinct asymmetry. This asymmetry appears to be due to a cloud of spirals with a redshift of $\sim$2000 km s^{-1} that is located behind the dense cluster core. This complexity of the Virgo region is unfortunate because, as Tully (1990) has emphasized, the distance to the Virgo region is such an

TABLE 13
Distance of the Virgo Cluster

Method	Author	ϵ_J	$(m-M)_0$
Planetary nebulae	Jacoby *et al.* (1990)	10.1	30.74 ± 0.05
Surface brightness fluctuations	Tonry *et al.* (1990)	10.5	30.86 ± 0.13
Tully-Fisher	Pierce & Tully (1988)	9.1	30.88 ± 0.2
Globular clusters	Harris *et al.* (1991)	5.2	31.47 ± 0.25
Novae	Capaccioli *et al.* (1990)	10.6	31.3 ± 0.36
Red supergiants in NGC 4571	Pierce *et al.* (1992)	10.4	30.7
Yellow supergiants in NGC 4523	Shanks *et al.* (1992)	10.4	30.6
SN 1979C in M 100	Schmidt *et al.* (1992)	10.2	31.4 ± 0.6
SN 1979C in M 58	Schmidt *et al.* (1992)	10.2	31.8 ± 0.4
c.f. Diameter of M 31		7.1	31.15 ± 0.35
c.f. Diameter of M 33		7.1	30.1 ± 0.5
c.f. Diameter of LMC		7.1	30.4 ± 0.5
			30.95 ± 0.14

important stepping stone along the difficult path that has to be followed in our quest for the numerical value of the Hubble parameter.

Observations of H I (Burstein and Heiles 1984) appear to indicate that there is little or no Galactic gas in the direction of the Virgo cluster. In the following discussion it has therefore been assumed that the Virgo cluster is unreddened. However, it should be noted that recent *IRAS* observations (Rowan-Robinson et al. 1991) show that there is some thin patchy Galactic cirrus that obscures parts of the Virgo region. Absorption values for individual galaxies in this region probably fall in the range $0.0 \leqslant A_V \leqslant 0.1$ mag.

10.1 Planetary Nebulae

Jacoby et al. (1990) have used the luminosity functions of planetary nebulae to determine distances to six luminous E and S0 galaxies in, or near, the core of the Virgo cluster. After applying a correction of -0.1 mag (see Sec. 2.1) to the distances of Jacoby et al., the mean Virgo distance modulus is found to be $\langle (m-M)_0 \rangle = 30.74 \pm 0.05$ ($D = 14.1$ Mpc). (This quoted mean error does *not* include the uncertainty in the adopted distance modulus of M31.) The dispersion in the distance moduli of individual galaxies about this mean is only 0.11 mag. Bottinelli et al. (1991) report finding a slight dependence of distance modulus on galaxy luminosity. This dependence is in the sense that the most luminous Virgo galaxies appear to have distance moduli that are about a quarter of a magnitude smaller than those of less luminous cluster members.

10.2 Supernovae

Schmidt et al. (1992) have obtained photometric and spectroscopic observations of two supernovae of Type II in the Virgo cluster. The distance moduli derived for these objects are listed in Table 13. These moduli are seen to be somewhat larger than those obtained using most other techniques.

The distance of NGC 5128 found in Sec. 4, in conjunction with the B and V observations of the Type-Ia supernova 1986G, yield $M_B(\max) = -19.7 \pm 0.15$. Similar observations of the Type-Ia supernova 1972E, in conjunction with a Centaurus group distance modulus 27.7 ± 0.5, yield $M_B(\max) = -19.4 \pm 0.5$. A significantly fainter value $M_B(\max) = -18.2$ is obtained for the Type-Ia supernova 1937C, if one adopts the distance modulus for its parent galaxy IC 4182 that has recently been derived by Pierce et al. (1992). This suggests that either (1) the adopted distance to IC 4182 is too small (Sandage and Tammann 1982), or (2) SN Ia exhibit a rather large dispersion in $M_B(\max)$.

According to van den Bergh (1993), the following are the absorption-corrected maximum magnitudes of supernovae of Type Ia in or near the Virgo cluster for which the observational errors are $\lesssim 0.5$ mag: 1957B $B_0(\max) = 12.0$, 1961H $B_0(\max) = 11.5$, 1971G $B_0(\max) = 14.0$, SN 1984A $B_0(\max) = 12.2$, SN 1990N $B_0(\max) = 12.6$, 1991T $B_0(\max) = 11.1$, and NGC 1991bg $B_0(\max) \simeq 14.9$. These objects are seen to exhibit a luminosity range of 3.8 mag. SN 1957B with $B(\max) = 12.0 \pm 0.5$ and SN 1991bg with $B(\mathrm{mag}) \simeq 14.9$ were both supernovae of Type Ia that occured in the E1 galaxy NGC 4374 (=M84). This shows that depth of the Virgo cluster along the line of sight cannot be the sole cause of the large observed dispersion in the luminosities of Virgo SN Ia at maximum light.

If one rejects SN 1991T and SN 1991bg because their spectra were peculiar, and if one also rejects SN 1971G because it *might* possibly have been of Type Ib, then the remaining three Virgo SN Ia have $\langle B_0(\max) \rangle = 12.1 \pm 0.25$. Comparison with SN 1972E (see Sec. 4), with $M_B(\max) = -19.7 \pm 0.15$, would then give a Virgo modulus $(m-M)_0 = 31.8 \pm 0.3$. On the other hand, comparison with SN 1937C, with $M_B(\max) = -18.2$, gives $(m-M)_0 = 30.3$ for the Virgo cluster. It is therefore tentatively concluded that the intrinsic dispersion in the luminosity of SN Ia is probably too large to yield a meaningful distance to the Virgo cluster.

10.3 Globular Clusters

Harris et al. (1991) find that the luminosity functions of the globular-cluster systems surrounding four giant elliptical galaxies in the Virgo cluster peak at $\langle B^0 \rangle = 24.77$, with a galaxy-to-galaxy scatter of ± 0.2 mag. Combining this with the value $M_B^0 = -6.7 \pm 0.15$ for Galactic halo globulars yields a Virgo cluster distance modulus $(m-M)_0 = 31.47 \pm 0.25$. [A distance modulus that is ~ 0.1 mag smaller would be obtained if NGC 4365 is omitted from the mean because it might (see Sec. 10.5) lie behind the cluster core.] The degree of trust that is placed in this Virgo cluster distance modulus depends on the amount of confidence felt in the assumption that the globular clusters surrounding spiral and elliptical galaxies have similar characteristics. The strongest evidence bearing on this point comes from Harris's (1990) observations of the globular clusters associated with NGC 3377 (E6) and NGC 3379 (E0), which yield $(m-M)_0 = 30.05 \pm 0.4$. For comparison, Ciardullo et al. (1989) obtained $(m-M)_0 = 29.9$ from observations of planetary nebulae in these galaxies, while Tonry (1990) derived $(m-M)_0=29.7$ from surface-brightness fluctuations. Clearly it would be very important to observe B^0 values for cluster systems in physically associated elliptical and edge-on spiral galaxies. This would allow one to check on the conclusion that the mean luminosity of globular clusters is independent of the Hubble type of their parent galaxy.

10.4 Brightest Red Supergiants

Pierce et al. (1992) have used the Canada-France-Hawaii Telescope, in seeing of $\sim$0.4 arcsec, to resolve the brightest red and blue supergiants in the Virgo Sbc II galaxy NGC 4571. The very low radial velocity $v_0=282$ km s^{-1} of this galaxy makes it virtually certain that this object is not associated with the cloud of spirals situated behind the Virgo cluster core. For the three brightest red supergiants, Pierce et al. (1992) find $\langle R(3)\rangle=21.6\pm0.1$. Adopting $V-R=1.1$ and $M_V(3)=-8.0$ this yields $(m-M)_R=30.7$. This result is marginally consistent with the observations of Tanvir et al. (1991) who, from their non-detection of resolved red supergiants in IC 3583, set a lower limit $(m-M)_R>30.7$ on the distance to the Virgo cluster.

Recently Shanks et al. (1992) have resolved the low-luminosity late-type galaxy NGC 4523 in the Virgo cluster. In this object the three brightest *yellow* supergiants have $\langle R(3)\rangle=21.0\pm0.3$. By adopting $M_R=-9.6$ for there objects Shanks et al. (1992) obtain $(m-M)_R=30.6$. Assuming no internal reddening in this low-luminosity object then yields $(m-M)_R\simeq(m-M)_0=30.6$ and hence $D\approx13$ kpc.

Could NGC 4523 ($v_0=198$ km s^{-1}) and NGC 4571 ($v_0=282$ km s^{-1}) be foreground galaxies projected on the Virgo cluster? If they are moving with the unperturbed Hubble flow these objects would be situated at only $\sim1/5$ of the distance of the core of the Virgo cluster itself, i.e., their distance moduli would be $\sim$3.5 mag smaller than that of the Virgo cluster proper. However, such a small distance can be excluded from the luminosity classification of NGC 4571. From DDO classification on CCD images, van den Bergh et al. (1990) derived a classification Sbc II. For 14 other Sb II, Sbc II, and Sc II galaxies in the Virgo and Ursa Major clusters these authors find $\langle B_T\rangle=12.06\pm0.24$, with a dispersion of 0.91 mag. This mean value is almost indentical to the value $B_T=12.1$ observed for NGC 4571 itself. Had NGC 4571 been an Sbc II foreground galaxy moving with the unperturbed Hubble flow one would instead have expected it to have $8\lesssim B_T\lesssim9$. It is therefore concluded that NGC 4571 is *not* a foreground object projected on the Virgo cluster.

Pierce et al. (1992) find $\langle R(3)\rangle=21.1\pm0.1$, corresponding to $V(3)=21.3$, for the third brightest *blue* supergiant in NGC 4571. Comparison with the brightest blue stars in M33, for which $M_V(2)=-9.6$ (Humphreys 1983), yields a Virgo distance modulus $(m-M)_v=30.9$. However, this value is less secure than that determined from red supergiants because (1) the luminosities of the brightest blue supergiants exhibits considerable scatter, and (2) the brightest blue "stars" are not always stars (Humphreys and Aaronson 1987).

A group led by Michael Pierce is presently using the Canada-France-Hawaii Telescope in an attempt to derive a distance modulus of the Virgo cluster from observations of long-period red supergiant variables (and hopefully also Cepheids) in NGC 4571.

10.5 Surface-Brightness Fluctuations

Tonry et al. (1990) list infrared fluctuation magnitudes $\bar{I}$, and integrated $V-I$ colors, for 10 E and S0 galaxies in the Virgo cluster. Substituting these data into Eq. (2) yields $\langle(m-M)_0\rangle=30.86\pm0.13$ ($D=14.9$ Mpc), with a dispersion $\sigma=0.4$ mag, for the Virgo cluster. If the E3 galaxy NGC 4365, for which $(m-M)_0=31.61$, is assigned to the background then $\langle(m-M)_0\rangle=30.78$. Some support for the hypothesis that NGC 4365 lies behind the Virgo cluster core is also provided by the globular-cluster observations of Harris et al. (1991) who find that the peak of the NGC 4365 luminosity function is 0.4 to 0.5 mag fainter than those of the well-observed cluster systems surrounding NGC 4472, NGC 4486, and NGC 4649.

Inspection of Table 13 shows that the distance modulus of the Virgo cluster obtained from surface-brightness fluctuations is in excellent agreement with distance moduli obtained using other techniques.

10.6 Novae in the Virgo Cluster

Pritchet and van den Bergh (1987b) have observed the light curves of seven novae that occured in giant elliptical galaxies in the core of the Virgo cluster. By combining these data with a revised maximum magnitude versus rate of decline relation Capaccioli et al. (1990) derive a difference between the true distance moduli of Virgo and M31 of $\Delta(m-M)_0=7.0\pm0.35$ mag. Combining this with the value $(m-M)_0=24.3\pm0.1$ for M31 (see Sec. 2.2) yields a Virgo distance modulus of $(m-M)_0=31.3\pm0.36$. Note that one of the seven novae observed by Pritchet and van den Bergh (1987b) was located in NGC 4365. *If* this galaxy is indeed situated behind the cluster core, then the distance modulus of the core of the Virgo cluster is $\sim$0.1 mag smaller than the value quoted above.

10.7 Virgo and the Hubble Parameter

Modern distance determinations to the Virgo cluster are summarized in Table 13. The real uncertainty of any individual method of distance determination is due to systematic effects rather than to statistical errors. It is therefore not meaningful to use a weighted mean distance based on the formal mean errors of each distance determination. Taking an unweighted mean of all 12 distance determinations listed in Table 13 yields $\langle(m-M)_0\rangle=30.95\pm0.14$. Perhaps a more reasonable approach is to combine the two distance determinations based on supernovae of Type II, the two distances based on red/yellow supergiants, and also the three determinations based on comparisons of galaxy diameters. One then finds that eight different methods of determining the distance to the Virgo cluster give $\langle (m-M)_0 \rangle = 31.01 \pm 0.14$. All eight methods yield individual distance moduli that lie in the range $30.55 \leqslant (m-M)_0 \leqslant 31.6$ (13–21 Mpc). In the subsequent discussion a value $(m-M)_0 = 31.0 \pm 0.15$ ($D = 15.8 \pm 1.1$ Mpc) will be adopted for the Virgo cluster.

In principle it should be possible to combine this distance with the mean redshift of Virgo cluster members to determine the numerical value of the Hubble parameter. In practice there are, however, three reasons why a value of H_0 determined in this simpleminded manner might be subject to significant systematic errors:

(i) The mean velocity of recession of the Virgo cluster is uncertain because inclusion of even a small number of members of the cloud of background spirals, on which the Virgo cluster core is projected, will affect the mean cluster velocity significantly. This problem can be minimized (but not entirely eliminated) by using the Tully–Fisher distances (Pierce and Tully 1988) and distances derived from luminosity classifications (van den Bergh et al. 1990) to eliminate background spirals.

(ii) The overdensity in the core of the Virgo supercluster retards the expansion of the local region of the Universe. Estimates of the magnitude of this retardation (infall) range from -90 to $+520$ km s^{-1} (Davis and Peebles 1983). This shows that the correction required to determine the cosmological redshift of the Virgo cluster is still quite uncertain. Precision distance determinations for large numbers of individual galaxies from planetary-nebula luminosity functions or surface-brightness fluctuations should, however, make it possible to determine the retardation of the Local Group that is produced by the Virgo supercluster more accurately in the not too distant future.

(iii) Large-scale deviations from a smooth Hubble flow (Burstein 1990; Bertschinger et al. 1990; Han and Mould 1990) are now believed to reach hundreds of km s^{-1}. Such velocity values are *not* small compared to the ~ 1000 km s^{-1} mean redshift of the Virgo cluster.

In view of these problems it seems best to determine the Hubble parameter from the distances and redshifts of compact isolated aggregates, such as the Coma cluster, which have redshifts that are an order of magnitude (or more) greater than likely deviations from a smooth Hubble flow.

Tully (1990) has shown that the distances of the Virgo cluster adopted by individual astronomers correlate strongly with the values of the Hubble parameter that they favor. Virgo distance moduli ~ 30.7 are invariably associated with larger values of H_0, whereas Virgo distance moduli ~ 31.7 always yield small values of the Hubble parameter. The value $(m-M)_0 = 31.0 \pm 0.15$ that was derived above for the Virgo cluster therefore hints at a value of H_0 in the upper half of the range of Hubble parameter values obtained during the last decade.

11. THE FORNAX CLUSTER

Tonry (1991) reports observations of the infrared fluctuation magnitudes and integrated $V-I$ colors for 13 galaxies in the Fornax cluster. From these data and Eq. (2) one obtains a mean distance modulus $\langle (m-M)_0 \rangle = 30.64 \pm 0.07$ and a dispersion of only 0.24 mag for distance determinations to individual cluster galaxies.

TABLE 14
Comparison of Present Distances with those of Sandage (1986)

Galaxy	$(m-M)_0$ present	$(m-M)_0$ Sandage	$\Delta(m-M)_0^a$
NGC 6822	23.66 ± 0.2	23.95	-0.29 ± 0.2
M 31	24.3 ± 0.10	24.12	+0.18 ± 0.10
IC 1613	24.42 ± 0.13	24.43	-0.01 ± 0.13
M 33	24.5 ± 0.2	24.7	-0.2 ± 0.2
Sextans A	25.27 ± 0.17	26.2	-0.93 ± 0.17
NGC 3109	25.4 ± 0.18	26.0	-0.6 ± 0.18
NGC 300	26.0 ± 0.2	26.1	-0.1 ± 0.2
Pegasus	26.08 ± 0.2	27	-0.92 ± 0.2
M 81	27.6 ± 0.15	28.8	-1.2 ± 0.15
Virgo Cl.	31.0 ± 0.2	31.7	-0.7 ± 0.2

[a] quoted errors do not include uncertainty in Sandage's moduli

From the assumption that the globular clusters in NGC 1399, which is the central galaxy of the Fornax cluster, have the same luminosity as those in the Galactic halo, it is found (cf. Sec. 5.2) that $(m-M)_0 = 31.5 \pm 0.5$. It is of interest to note that this distance modulus is somewhat larger than that obtained using Tonry's surface-brightness fluctuation method. A (marginally significant) difference in the same sense between the distance moduli obtained by these two techniques was previously found for the Virgo cluster.

12. THE ERIDANUS CLUSTER

Tonry (1991) has reported infrared surface-brightness fluctuations and integrated $V-I$ colors for five galaxies in the Eridanus cluster. Using these values, in conjunction with Eq. (2), yields $(m-M)_0 = 30.96 \pm 0.03$, with a (fortuitously small) dispersion of only 0.06 mag.

13. THE "LONG" VERSUS THE "SHORT" DISTANCE SCALE

Table 14 and Figs. 7 and 8 show a comparison between the distances to individual galaxies, groups, and clusters derived in the present investigation with those adopted by Sandage (1986). These data show, as has previously been emphasized by de Vaucouleurs (1993), that the systematic differences between the "long" and the "short" distance scales start quite abruptly near Sandage's $(m-M)_0 \simeq 27$. It should therefore be possible to solve, what is traditionally regarded as the distance-scale problem, at quite modest distances of 3–10 Mpc. *It is important to note that the classical distance-scale problem is entirely unrelated to the galaxian velocity field.* It seems likely that many (but not all) of the differences between recent distance moduli, and those compiled by Sandage (1986), are due to problems with photographic photometry and faint magnitude sequences. Such difficulties are, of course, largely avoided in modern work using CCD detectors. A classic example of such problems is provided by Sandage and Carlson (1983),

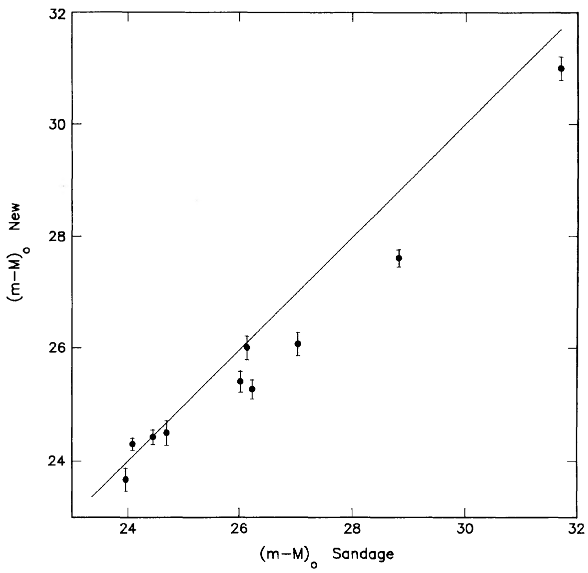

FIG. 7—Comparison between distances derived in the present review and those adopted by Sandage (1986). The figure shows that significant systematic differences occur for Sandage moduli $\gtrsim 27$.

who found a distance modulus to M33 that is now known to have been too large by 0.7 mag.

A similar trend, albeit with lower weight, is seen in the cases of M83 and IC 4182. Sandage and Tammann (1974b) used H II region diameters to derive $(m-M)_0 = 29.74$ for M83, which is significantly larger than the value $(m-M)_0 = 28.4 \pm 0.4$, which Schmidt et al. and Eastman (1992) calculate from the photospheric expansion of SN 1968L and the Centaurus group modulus $(m-M)_0 = 27.7 \pm 0.5$ derived in Sec. 3.4. Note, however, that van den Bergh (1980) has shown that the H II region distances derived by Sandage and Tammann (1974b) are, at least in part, based on circular reasoning. In the case of IC 4182, Sandage and Tammann (1982) used *photographic* photometry of the brightest supergiants to obtain $(m-M)_0 = 28.2 \pm 0.3$. A similar study using CCD photometry (Pierce et al. 1992) yields $(m-M)_0 = 27.0 \pm 0.2$. The difference $\Delta(m-M)_0 = -1.2 \pm 0.4$ is in the same sense as the other values for this difference that are listed in Table 13.

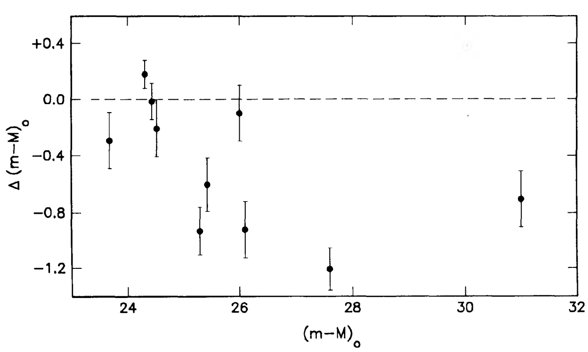

FIG. 8—Differences between new and Sandage moduli vs new distance moduli.

It should be emphasized that the technically difficult problem of actually determining the numerical value of the Hubble parameter will have to be resolved at redshifts that are an order of magnitude greater than typical deviations from a smooth Hubble flow.

14. THE COMA CLUSTER

The Coma cluster (A 1656) is a rich cluster of Bautz–Morgan Type II. It is particularly suitable for the determination of the Hubble parameter because it is reasonably well isolated in redshift space (Tifft and Gregory 1976), and because its peculiar velocity relative to the Hubble flow is likely to be small compared to its redshift of ~ 7000 km s^{-1}. An additional advantage enjoyed by the Coma cluster is that it is located almost perpendicular to the direction of the large-scale streaming motion that appears to extend from Pisces-Perseus to Hydra-Centaurus (Mathewson et al. 1992).

Because of its great distance, direct determinations of the distance to the Coma cluster are exceedingly difficult. Globular clusters have been detected in Coma ellipticals (Harris 1987; Thompson and Valdes 1987), but the peak of the cluster luminosity function remains well beyond the limits of current observational technology. Tammann (1978), Capaccioli et al. (1990), and Fukugita and Hogen (1991) have tried to use SN Ia to establish the distance to the Coma cluster. However, confidence in these results is undermined by mounting evidence for a large luminosity dispersion among SN Ia (see Sec. 8.1 and van den Bergh 1993). Finally, Aaronson (1986), Bottinelli et al. (1987), Kraan-Korteweg et al. (1988), Fukugita et al. (1991), and Rood and Williams (1992) have attempted to use the Tully–Fisher relation to determine the distance of the Coma cluster. Due to differing calibrations, and corrections for incompleteness and for Malmquist bias, these authors obtain Coma distance moduli that fall in the very wide range $33.8 \leqslant (m-M)_0 \leqslant 35.7$. A more profitable approach (Sandage 1972) would appear to be use of the *difference* between the distance moduli of the Coma and Virgo cluster, in conjunction with the Virgo distance found in Sec. 10, to determine the distance to the Coma cluster. Differences between the Tully–Fisher distance moduli of Coma and Virgo determined by Aaronson et al. (1986), Giraud (1986), and Rood and Williams (1992) are listed in Table 15.

It was first pointed out by Sandage (1972) that the strong dependence of the $U-B$ colors of early-type galaxies on luminosity can be used to estimate the *difference* between the distance moduli of the Coma and Virgo clusters. From observations of E and S0 galaxies in these two clusters, Sandage obtained a difference in distance modulus $\Delta(m-M)_0 = 3.66 \pm 0.14$ mag. Subsequently Aaronson et al. (1981) found $\Delta(m-M)_0 = 3.5 \pm 0.2$, 3.0 ± 0.2, and 2.6 ± 0.3 mag from observations in $U-V$, $U-K$, and $V-K$, respectively. Aaronson et al. (1981) interpreted these differences to mean that the color-luminosity relations were not universal and differed from cluster to cluster. More recently Bower et al. (1992b) have, however, shown

TABLE 15
Difference Between Coma and Virgo Distance Moduli

Method	Reference	$\Delta(m-M)_0^a$
V vs. U-B	Sandage (1972)	3.66 ± 0.14
H-band T-F	Aaronson *et al.* (1986)	3.69 ± 0.16
B, H T-F	Giraud (1986)	3.70 ± 0.17
L(r) vs. σ_r	Lucey (1986)	3.76 ± 0.12
Mass vs. luminosity	Vader (1986)	3.4 - 3.8
D_n vs. σ_r (ellipticals)	Dressler *et al.* (1987)	3.65
D_n vs. σ_r (spiral bulges)	Dressler (1987)	3.67
D_n vs. Mg_2	Dressler *et al.* (1987)	3.99
Reduced radii	Gudehus (1991)	4.07
T-F (M31-like)	Rood & Williams (1992)	3.42 ± 0.22
E + S0 (UVJK σ_r)	Bower *et al.* (1992b)	3.70 ± 0.09
E (UVJK σ_r)	Bower *et al.* (1992b)	3.59 ± 0.06
	Adopted	3.71 ± 0.05

[a] Both Virgo and Coma assumed unreddened

that these differences were probably due to inhomogeneity of the optical photometry of Aaronson et al. (1981) and to measuring errors in infrared photometry of the faintest Coma galaxies. From new *UVJK* photometry of E and S0 galaxies in the Virgo and Coma clusters, Bower et al. (1992a,b) conclude that Virgo and Coma galaxies follow the same $U-V$ and $V-K$ color-luminosity (and color-diameter) relations to within 0.04 mag.

For E and S0 galaxies, Bower et al. (1992b) find $\Delta(m-M)_0=4.01$, 3.58, and 3.62 mag, respectively, from the relations between total apparent visual magnitude V_T and $U-V$, $V-K$, and $\log \sigma_r$. For E galaxies only, the corresponding values are $\Delta(m-M)_0=3.77$, 3.38, and 3.58, respectively. For E and S0 galaxies, $\log D_V$ vs $U-V$, $V-K$, and $\log \sigma_r$ yield $\Delta(m-M)_0=3.87$, 3.42, and 3.67 mag, respectively, while E galaxies give $\log D_V$ vs $U-V$, $V-K$, and $\log \sigma_r$ values of $\Delta(m-M)_0=3.72$, 3.50, and 3.60 mag, respectively. The relations for E and S0 galaxies give a formal mean $\langle\Delta(m-M)_0\rangle=3.70\pm0.09$ mag, while for E galaxies alone the corresponding value is $\langle\Delta(m-M)_0\rangle=3.59\pm0.06$.

From a comparison of the D_n-vs-σ_r relations for elliptical galaxies in the Virgo and Coma clusters, Dressler et al. (1987) find $\Delta(m-M)_0=3.65$ mag. Confidence in this result is somewhat reduced by the fact that Lucey et al. (1991b) find the ellipticals in Coma and Virgo to lie on intrinsically different fundamental planes. However, more recent work by Lucey et al. (1991) does not appear to support the conclusion that Virgo and Coma ellipticals are intrinsically different. From the D_n-vs-Mg_2 relation, Dressler et al. (1987) find a somewhat larger value $\Delta(m-M)_0=3.99$ mag.

Vader (1986) has used a comparison between the mass-luminosity relations for ellipticals in Coma and Virgo to derive a value $\Delta(m-M)_0=3.8$ mag. Her analysis suggests that Coma ellipticals are less compact than Virgo ellipticals. If this effect is, in fact, due to a systematic overestimate of the radii of faint Coma ellipticals in the RC2 (de Vancouleurs et al. 1976), then the true value of $\Delta(m-M)_0=3.4$ mag.

A rather large value $\Delta(m-M)_0=4.07$ has been derived by Gudehus (1991) from his "reduced radii" method. Finally Lucey (1986) has found that the relation between the velocity dispersion and the luminosity $L(r)$ through relatively small fixed metric apertures appears to exhibit less dispersion than does the correlation between velocity dispersion and total luminosity of elliptical galaxies. From the $L(r)$ vs $\log \sigma_r$ relations for the Virgo and Coma clusters, Lucey (1986) finds $\Delta(m-M)_0=3.76\pm0.12$ mag.

All of the values of $\Delta(m-M)_0$ discussed above are listed in Table 15. An *unweighted* mean of all these results yields $\langle(m-M)_0\rangle=3.71$. Eight out of the 12 values listed in the table lie in the range $3.60\leqslant(m-M)_0\leqslant3.82$. In the subsequent discussion it will be assumed that the difference between the true distance moduli of the Coma and Virgo clusters is $\Delta(m-M)_0=3.71\pm0.05$ mag. Combining this value with the Virgo modulus $(m-M)_0=31.0\pm0.15$ obtained in Sec. 10 yields a Coma distance modulus $(m-M)_0=34.7\pm0.16$ corresponding to a distance of 87 ± 6 Mpc. It is a tribute to the power of differential techniques that the value $\Delta(m-M)_0=3.71\pm0.05$ mag obtained above is entirely consistent with $\Delta(m-M)_0=3.66\pm0.14$ obtained 20 years ago by Sandage (1972).

From a discussion of available radial-velocity data, Fukugita et al. (1991) conclude that the mean heliocentric velocity of the Coma cluster is $v_0=6925$ km s^{-1}. After correcting this value for a Virgocentric infall velocity of 300 ± 100 km s^{-1}, they obtain a cosmological velocity of 7210 km s^{-1} for the Coma cluster. Using slightly different input parameters, Staverley-Smith and Davies (1989) obtained a cosmological velocity of 7203 ± 45 km s^{-1} for the Coma cluster. Combining a radial velocity of 7210 km s^{-1} with a distance of 87 ± 6 Mpc yields a Hubble parameter $H_0=83\pm6$ km s^{-1} from the Coma cluster. It is noted in passing that $H_0=83\pm6$ km s^{-1} Mpc^{-1} and $D=15.8\pm1.1$ Mpc yield an expected cosmological redshift of $v=1311\pm132$ km s^{-1} for the Virgo cluster. This compares to an observed heliocentric cluster velocity of $\langle v_0\rangle=1099$ km s^{-1}, which Huchra (1985) obtained after first eliminating a clump of probable background galaxies. These data are therefore compatible with a Local Group retardation of a couple of hundred km s^{-1}.

15. THE GLOBAL HUBBLE PARAMETER

A number of recent investigations (Willick 1990; Mould et al. 1991; Mathewson et al. 1992; Ichikawa and Fukugita 1992; Shaya et al. 1992) have shown that systematic deviations from a smooth Hubble flow may occur over scales of tens of Mpc. Furthermore, Turner et al. (1992) have suggested that large systematic differences might exist between the local and the global value of the Hubble parameter.

An excellent database for the study of possible systematic differences between the local and global values of the Hubble parameter in provided by Hoessel et al. (1980). These authors give magnitudes, colors, and redshifts for a complete sample of first-ranked galaxies in Abell clusters of richness class $\geqslant1$ and distance class $\leqslant4$. The redshifts of these objects fall in the range $0.02\lesssim z\lesssim0.15$. For the first-

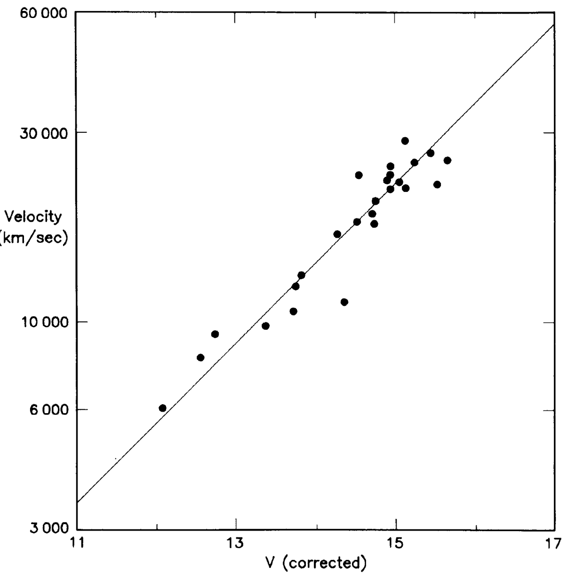

FIG. 9—Velocity-distance relation for brightest galaxies in Abell clusters of Bautz-Morgan Types I and I-II. The fact that the galaxies in clusters with redshifts $< 10{,}000$ km s^{-1} lie close to the regression line given by Eq. (3) shows that H_0(local) does not differ significantly from H_0(global).

ranked galaxies in clusters of Bautz-Morgan (1970) classes I and I-II it is found (see Fig. 9) that

$$M_V = -21.73 \pm 0.06 + 5 \log h, \qquad (3)$$

in which $h = H_0/100$ km s^{-1} Mpc^{-1}.

According to van den Bergh (1993), the dispersion of individual galaxies about the mean luminosity given by Eq. (3) is only 0.31 mag. The clusters A 496 (MB I), A 779 (BM I-II), A 2199 (BM I), and A 2666 (BM I) contained in the compilation of Hoessel et al. (1980) have redshifts $< 10{,}000$ km s^{-1}. These four clusters, on average, lie 0.14 ± 0.17 mag to the left of the regression line shown in Fig. 9. (The quoted error includes the ± 0.06 mag uncertainty in the zero point of the adopted regression line.) This result implies that $H_0(\text{global}) = (0.94 \pm 0.07)\ H_0(\text{local})$, in which H_0(local) is defined to be the Hubble parameter for the region with $v_0 < 10{,}000$ km s^{-1}. The three nearest clusters of BM Types I and I-II, in which the first-ranked galaxy has V(corrected) < 13.0, on average lie 0.25 ± 0.19 mag to the left of the regression line shown in Fig. 9. From these three clusters one therefore obtains H_0(global) $= (0.89 \pm 0.08)\ H_0$(local). Adopting $H_0(\text{local}) = 83 \pm 6$ km s^{-1} Mpc^{-1} (see Sec. 13) and $H_0(\text{global}) = (0.92 \pm 0.08)\ H_0(\text{local})$ finally yields $H_0(\text{global}) = 76 \pm 9$ km s^{-1} Mpc^{-1}. This determination of the ratio $H_0(\text{global})/H_0(\text{local})$, and hence the accuracy of H_0(global), could be increased significantly by extending the photometric observations of northern Abell (1958) clusters by Hoessel et al. (1980) to the southern clusters cataloged by Abell et al. (1989). It should, of course, be emphasized that the present finding that H_0(global) $= (0.92 \pm 0.08)\ H_0$(local) does *not* constitute detection of a significant difference between the local and global values of the Hubble parameter.

16. NONCONVENTIONAL DETERMINATIONS OF H_0

16.1 Virial Distances

Galactic masses determined from rotation curves scale as $M \propto D$, whereas gas masses and stellar masses (derived from assumed M/L ratios) scale as $M \propto D^2$. Staverley-Smith et al. (1990) have used this fact to derive a distance to the gas-rich dwarf galaxy UGC 12578. They conclude that $H_0 = 70 \pm 7$ km s^{-1} Mpc^{-1}, if this galaxy contains no dark matter. However, if dark matter is present in a manner that mimics one of the observed components, then this result should be strictly interpreted as a 95% confidence level lower limit on the Hubble parameter of 59 km s^{-1} Mpc^{-1}.

16.2 Nickel in Supernovae of Type Ia

The luminosity of SN Ia depends on the amount of ^{56}Ni that is synthesized during during their detonation. From theoretical calculations, which favor the formation of ~ 0.6 $M_\odot$ of ^{56}Ni, Arnett et al. (1985) obtained $H_0 = 59 \pm 14$ km s^{-1} Mpc. Using the same technique, Branch (1992) has more recently derived a value of $H_0 = 68 \pm 11$ km s^{-1} Mpc^{-1}. Note, however, that Ruiz-Lapuente et al. (1992) have derived a ^{56}Ni mass of only 0.38 ± 0.03 $M_\odot$ from observations of the Type-Ia supernova 1986G. With this lower Ni mass, supernovae of Type Ia will be fainter, resulting in a larger value of H_0.

16.3 Time Delays and Gravitational Lensing

Refsdal (1964, 1966) first showed that the time delay between light variations seen in multiple images of the same quasar can, in principle, be used to derived H_0. Observations of the gravitational lens Q 0957+561, in which the time delay between the components is observed to be 536 ± 12 days, have recently been reviewed by Narayan (1991). To obtain a value of H_0 from these observations will require knowledge of the density distribution in the cluster surrounding the galaxy which lenses Q 0957+561. This density distribution might, in principle, be derived from observations of luminous arcs produced by lensing of background galaxies. From an analysis of presently available data on Q 0957+561, Kochanek (1991) finds $H_0 \lesssim 90$ ± 30 km s^{-1} Mpc^{-1}.

Recently Soucail and Fort (1991) have interpreted the velocity gradient along a luminous arc in the cluster A 2390 as being due to rotation in a lensed background galaxy. By applying the Tully–Fisher relation to this object, Soucail and Fort find $H_0 = 95 \pm 26$ km s^{-1} Mpc for $q_0 = 0$, or $H_0 = 75 \pm 20$ km s^{-1} Mpc^{-1} for $q_0 = 0.5$.

16.4 X-Ray Clusters

Silk and White (1978) have shown that X-ray observations of hot cluster gas, together with the decrement in the observed brightness of the microwave background due to Compton scattering of photons passing through hot cluster gas (Sunyaev and Zel'dovich 1972), provide a method for determining both H_0 and q_0. Application of this technique to the cluster A 2218 (McHardy et al. 1990) yields $H_0=24^{+13}_{-10}$ km s^{-1} Mpc^{-1}, whereas $H_0=(40$ to $50)$ ± 12 km s^{-1} Mpc is found for the cluster A 665 (Birkinshaw et al. 1991). It is not yet clear if these very low values of H_0 are due to clumping of gas, errors in the X-ray temperature determinations, or systematic bias in the microwave decrement observations. Additional problems might arise from asphericity of the cluster, motion of the cluster relative to the smooth Hubble flow, and clumping of the intracluster gas.

17. THE AGE OF THE UNIVERSE

The age of the Universe can be estimated from abundance ratios of radioactive elements, from the cooling times of white dwarfs, and from the evolutionary ages of the oldest stars and star clusters.

In a recent review, Cowan et al. (1991) conclude that nuclear chronology permits acceptable estimates for the Galactic age in the range 10–20 Gyr. That this age range is so wide is mainly due to the fact that ages derived from isotope ratios are sensitive to the poorly known time dependence of the rate of star formation and, to a lesser extent, on uncertainties in the production ratios of radioactive isotopes.

It was first pointed out by Schmidt (1959) that the luminosity function of white dwarfs contains important information on the ages and evolutionary history of stellar populations in the Galactic disk. Recent parallax observations by Monet et al. (1992) provide striking evidence for a sharp cutoff in the luminosity function of white dwarfs near $M_V=+16$. Wood (1992) used this information to calculate a maximum cooling age of 7.5–11 Gyr for white dwarfs in the Galactic disk. Recently Xu and Van Horn (1992) have, however, pointed out that this maximum age might increase to ~ 13 Gyr if C/O, Fe/C, and Ne/C phase separation takes place in white dwarfs. Furthermore, Pitts and Tayler (1992) have emphasized the fact that some gas may have existed in the Galactic disk ~ 1 Gyr before star formation reached a significant level. In any case the age estimates of the Galactic disk from the cooling times of white dwarfs are consistent with the ~ 7.5 Gyr age estimate (Demarque et al. 1992) for the oldest known open cluster in the disk of the Galaxy.

The ages of the oldest globular clusters belonging to the Galactic halo remain controversial. Chaboyer et al. (1992) find that oldest globulars have an age of 17 ± 2 Gyr, while Proffitt and Michaud (1991) derive ages as short as 12 Gyr. In particular Proffitt and van den Berg (1991) find an age of 14 ± 2 Gyr for the old halo cluster M92, while Chaboyer et al. (1992) obtain an age of 16 ± 2 Gyr for the same object. In summary, it appears that ages of the oldest Galactic halo globular clusters probably lie in the range 12–17 Gyr. Allowing ~ 1 Gyr for the proto-Galaxy to collapse one then obtains an age of the Universe of 13–18 Gyr. For the "standard" cosmological model with $\Omega=1$ and $\Lambda=0$ the age of the Universe derived from globular cluster ages corresponds to $36 \leqslant H_0 \leqslant 50$ km s^{-1} Mpc^{-1}. The observed value of H_0(global) derived in Sec. 15 differs from that predicted by theories of stellar evolution, in conjunction with canonical models of the Universe having $\Omega=1$ and $\Lambda=0$, at the $\sim 3\sigma$ level.

18. CONCLUSIONS

(i) Distances to members of the Local Group now appear to be quite well determined with uncertainties of only 0.10–0.15 mag in the distance moduli of the LMC, SMC, M31, and M33. The corresponding uncertainties in their individual distances are $<10\%$. Confidence in these results is strengthened by the excellent agreement between distances derived from Population I and Population II distance indicators.

(ii) The luminosity function of Local Group galaxies derived from the best presently available distances fits a Schechter function with $\alpha=-1.1$. Down to $M_V \simeq -8$ there is no evidence for a low-luminosity cutoff in the galaxian luminosity function.

(iii) Distances are derived for the Sculptor, M81, Centaurus, M66+M96, M101, and NGC 1023 groups.

(iv) The present data (also see van den Bergh 1993) cast doubt on the usefulness of SN Ia as calibrators of the extragalactic distance scale.

(v) Eight different methods of distance determination give an unweighted mean distance modulus $\langle (m-M)_0 \rangle = 31.0\pm 0.15$ ($D=15.8\pm 1.1$ Mpc) for the Virgo cluster. The distance moduli derived from planetary nebulae, surface-brightness fluctuations, and the Tully–Fisher relation are 0.1–0.3 mag smaller than this mean value. Two SN II give distance moduli that are 0.4 ± 0.6 and 0.8 ± 0.4 mag larger than this average. The luminosity functions of Virgo globular clusters give a distance modulus that is 0.47 ± 0.25 mag larger than the average Virgo modulus quoted above. As noted in Sec. 10.5 this deviation would be reduced by ~ 0.1 mag if NGC 4365 lies behind the core of the Virgo cluster.

(vi) Comparison between the present distance scale and that of Sandage (1986) shows good agreement for $D \lesssim 3$ Mpc. Most (but not all) of the differences at larger distances are probably due to systematic errors of photographic magnitudes scales at faint magnitudes (which are much reduced in modern CCD photometry) and to excessive corrections for Malmquist bias.

(vii) Individual determination of the difference between the distance moduli of the Coma and Virgo clusters are found to be in excellent agreement. Eight out of 12 methods give $3.60 \leqslant \Delta(m-M)_0 \leqslant 3.82$. An unweighted mean of all determinations yields $\langle \Delta(m-M)_0 \rangle = 3.7\pm 0.13$. Together with a Virgo distance modulus of $(m-M)_0=31.0$ ± 0.15 this gives a distance modulus $(m-M)_0=34.7\pm 0.2$ ($D=87\pm 6$ Mpc) for the Coma cluster.

(viii) When combined with a cosmological redshift of 7210 km s^{-1} for the Coma cluster this distance yields a Hubble parameter H_0(local)$=83\pm 6$ km s^{-1}.

(xi) The velocity-distance relation derived from photometry of first-ranked galaxies in a complete sample of Abell clusters of Types BM I and BM I-II, of richness class

$\geqslant 1$, and in distance class $d \leqslant 4$ yields $H_0(\text{global})/H_0(\text{local}) = 0.92 \pm 0.08$, in which "local" refers to objects with $v < 10{,}000$ km s^{-1}.

(x) From the results in (viii) and (ix) a value $H_0(\text{global}) = 76 \pm 9$ km s^{-1} Mpc^{-1} is obtained.

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