Limits to the extragalactic distance scale from integrated properties of local group galaxies
by David John Westpfahl

A thesis submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy in Physics
Montana State University

Abstract:
Integrated properties, magnitudes and isophotal diameters, of the Local Group galaxies M31 and M33 are used to set upper and lower limits to the extragalactic distance scale in the direction of the Virgo cluster and the Ursa Major cluster. The assumption is made that M31 should not be larger or brighter than the largest, brightest cluster members, so a lower limit to the distance modulus of the cluster can be calculated. This gives an upper limit to Hubble's constant. It is also assumed that M33 should not be smaller or fainter than the smallest, faintest cluster members, so an upper limit to the distance modulus can be calculated. This gives a lower limit to Hubble's constant.

Data are collected in three systems with several correction schemes, and cluster membership lists are compared to determine the largest, brightest, smallest, and faintest members. The data are used to justify the assumptions necessary for the calculations.

The results depend upon the radial velocities of the clusters, which are in dispute. If the velocity of both clusters is 1100 km/s then the upper limit to Hubble's constant for the Virgo cluster is 90 ± 10 km/(s*Mpc) if NGC 4569 is accepted as the largest, brightest member, or 80 ± 9 if NGC 4321 is accepted. The lower limit depends upon the small, faint galaxy for comparison, but is at least 30±4 km/(s*Mpc) and may be as high as 47±5. The limits are the same for the Ursa Major cluster.

The method is applied to groups of galaxies seen in projection behind the Virgo and Ursa Major clusters, and to groups in the direction opposite to the clusters. It is concluded many small groups have a component of motion toward the clusters, relative to a uniform Hubble flow. This is attributed to the gravitational influence of the clusters, which extends to 25 Mpc if H is 100 km/(s*Mpc).

LIMITS TO THE EXTRAGALACTIC DISTANCE SCALE FROM INTEGRATED PROPERTIES OF LOCAL GROUP GALAXIES

by

David John Westpfahl Jr.

A thesis submitted in partial fulfillment
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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date

Co-chairperson, Graduate Committee

May 20, 1985
Date

Co-chairperson, Graduate Committee

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May 21, 1985
Date

Head, Major Department

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Date _16 May 1985_

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ABSTRACT

Integrated properties, magnitudes and isophotal diameters, of the Local Group galaxies M31 and M33 are used to set upper and lower limits to the extragalactic distance scale in the direction of the Virgo cluster and the Ursa Major cluster. The assumption is made that M31 should not be larger or brighter than the largest, brightest cluster members, so a lower limit to the distance modulus of the cluster can be calculated. This gives an upper limit to Hubble's constant. It is also assumed that M33 should not be smaller or fainter than the smallest, faintest cluster members, so an upper limit to the distance modulus can be calculated. This gives a lower limit to Hubble's constant.

Data are collected in three systems with several correction schemes, and cluster membership lists are compared to determine the largest, brightest, smallest, and faintest members. The data are used to justify the assumptions necessary for the calculations.

The results depend upon the radial velocities of the clusters, which are in dispute. If the velocity of both clusters is 1100 km/s then the upper limit to Hubble's constant for the Virgo cluster is 90 $\pm$ 10 km/(s*Mpc) if NGC 4569 is accepted as the largest, brightest member, or 80 $\pm$ 9 if NGC 4321 is accepted. The lower limit depends upon the small, faint galaxy for comparison, but is at least 30 $\pm$ 4 km/(s*Mpc) and may be as high as 47 $\pm$ 5. The limits are the same for the Ursa Major cluster.

The method is applied to groups of galaxies seen in projection behind the Virgo and Ursa Major clusters, and to groups in the direction opposite to the clusters. It is concluded many small groups have a component of motion toward the clusters, relative to a uniform Hubble flow. This is attributed to the gravitational influence of the clusters, which extends to 25 Mpc if H is 100 km/(s*Mpc).

CHAPTER 1

INTRODUCTION

The Need for an Extragalactic Distance Scale

The earliest astronomers were able to specify the direction to a star by giving its apparent position on the heavenly sphere. Modern astronomers do essentially the same thing, using the well-defined angles of declination and right-ascension to specify an apparent position. For many centuries men believed that the heavenly sphere was, in fact, a giant sphere made of some familiar materials and suspended about the Earth. Our present, less romantic, understanding is that the Earth and Sun occupy a typical region of our galaxy, the Milky Way, and the stars which we see are other residents of the Milky Way. Telescopes reveal other galaxies, presumably much like our own, spread across the sky.

Understanding the distribution of stars and galaxies in this system involves specifying not only a direction, but also a distance to any celestial object. Knowing how to measure distances to stars allows detailed mapping of our own Milky Way and the calculation of distances to the galaxies whose individual stars may be resolved.

Theoretical knowledge of the nature of space has put modern astrophysicists in the surprising position of being able to calculate general outlines of the past and future evolution of the Universe, provided a scale of distances among galaxies in the presently-observable universe is known.

Unfortunately, constructing a well-accepted scale of such distances (usually called an extragalactic distance scale because it applies outside the Milky Way) is a slow business. Any object included as part of the construction is in optimum position for observation only two or three months a year, but in half of each month accurate observations are impossible because the bright moon lights the entire sky. The problem is compounded because observers must compete with each other for use of telescopes, so nobody is able to use a large telescope for more than a few nights a month. Observing is also dependent on clear weather, so a week of cloudy nights might ruin an astronomer's entire observing season. Even if the weather is clear and the observations ideal, constructing an extragalactic distance scale is still a bootstrap process which must be tried, refined, and tried again, requiring many observations to iron out each difficulty.

The problem of calibrating distance indicators for use in defining the extragalactic distance scale has fascinated many of the best-known astronomers of the twentieth century, and often challenged their skills at the telescope. Since the first distance-scale calculations, about seventy years ago, the accepted distances to most galaxies have been steadily increasing. At present the distances are certain only to within a factor of two.

The extragalactic distance scale is most often specified by Hubble's constant. Hubble (1926) found that the distance to a galaxy increases linearly with its observed radial velocity (often expressed as the well-known redshift). This relationship is now written as $V = H*d$, where d is the distance to a galaxy in units of megaparsecs, V is the radial velocity in kilometers per second, and H is Hubble's constant in units of km/(s*Mpc). Readers unfamiliar with megaparsecs and other astronomical quantities, such as magnitudes and distance moduli, may wish to read Appendix A before proceeding with the body of this paper.

The Present Problem--Using the Integrated Properties of Local Group Galaxies to set Limits to the Distance Scale

In his review of recent work on the distance scale Hodge (1981) argues convincingly that the problems with the present understanding of extragalactic distances are symptomatic of a field in its youth, and that such a field should be expected to yield initially uncertain and confusing results. Taking this warning into account, but being unwilling to put off the problem of the distance scale altogether, our present understanding should allow the calculation of acceptable upper and lower limits to the distance scale and Hubble's constant. These limits may eliminate some of the values now considered plausible.

For the purposes of this study the integrated properties of Local Group galaxies are taken to be the apparent magnitude and angular diameter in optical light. Similar properties can be defined at other wavelengths, for instance in the radio spectrum, but such properties will not be considered in this paper.

If the integrated properties, diameters and magnitudes, of Local Group spiral galaxies can be determined without reference to the extragalactic distance scale, then limits to Hubble's constant may be set by a "Copernican" argument. The argument asserts that Local Group members are not the largest, smallest, brightest, or faintest spirals known, and that they should be no larger than the largest spirals in distant, highly-populated groups, as well as no brighter than the brightest, no smaller than the smallest, and no fainter than the faintest. This assertion is simply a variation of the Cosmological Principle, and some similar assumption must be made in all distance scale calculations. A lower limit to the distance scale results by calculating the distance to a group of galaxies under the assumption that the largest, brightest Local Group spiral is equal in size and brightness to the largest, brightest member of the distant group. An upper limit to the distance scale result from a similar assumption about the smallest, faintest spirals.

The appeal of calculating limits to the distance scale with this method is its simplicity, and every effort will be made to maintain this simplicity throughout this paper. Such calculations with integrated properties have been done only a few times, only with small data sets, and only to establish values of H or upper limits. In the present paper a large data set will be gathered and used to calculate both upper and lower limits. Tammann (1976, 1977) has compared 14 type Sb I-II field spiral galaxies with the Milky Way and M31, and finds $H \leq 60 \pm 15$ km/(s*Mpc), although this value includes the results of calculations which use two integrated properties no longer accepted as valid distance indicators. The radius of rotation curve turnover is no longer accepted as a distance indicator because the rotation curves of most spirals do not turn over. The mass-to-light ratio is recognized as containing distance information, but its sensitivity to star formation history makes it an unreliable indicator. The two calculations which remain, using angular diameters and apparent magnitudes as indicators, give upper limits to H of 77 $\pm$ 10 km/(s*Mpc) and 62 $\pm$ 10 km/(s*Mpc) respectively, but the systems of data and corrections are not specified.

Burbidge (1977) reported on earlier work by Burbidge and Hoyle in which a similar calculation using angular diameters gave H = 75 km/(s*Mpc) in the direction of the Hercules cluster. More recently de Vaucouleurs (1982a) has used five properties of the Milky Way to calibrate distance scales, all of which are significantly more complex than the calculations of Tammann (1976, 1977) and Burbidge (1977). Nonetheless, all suggest a "short" distance scale (a high value of Hubble's constant) with H = 95 $\pm$ 10 km/(s*Mpc).

In the present paper M31, the largest, brightest Local Group member, and M33, the smallest, faintest Local Group member, will be compared with spiral galaxies in the Virgo cluster, the Ursa Major cluster, and other small groups seen in projection behind them, to calculate limits to the distance scale. These comparisons will provide upper and lower limits to the distance scale in the direction of the clusters only. In calculating limits to H one must be aware of the well-known component of motion of the Local Group (relative to a uniform Hubble flow) in the direction of Virgo, observed early on by Gudehus (1973) and reviewed by Davis and Peebles (1983). For this reason Hubble's constant will be written as H, not as H_o which would imply a global value.

Although limits to Hubble's constant in several directions will be calculated, a value of Hubble's constant will not be calculated in this paper. To do so would require choosing one or more galaxies which have the same intrinsic properties as M31 and one or more having the same intrinsic properties as M33. While interesting choices are possible, all are difficult to justify in detail without making assumptions about the distance scale. A value of Hubble's constant might also be calculated by comparing the distribution of galaxy magnitudes in the Local Group with the distribution in distant clusters using the function of Schechter (1976). This will not be done because a value of H = 50 km/(s*Mpc) was assumed in deriving the distribution function, and because such a calculation would involve too much complexity for this paper. Instead of such calculations, diameter and magnitude histograms of Virgo galaxies will be plotted and arrows will be inserted to show where M31 and M33 would fall in the distributions for several values of the Virgo distance modulus, μ_V.

The Milky Way will not be included in these calculations, although this could be done using the description of the Galaxy given by de Vaucouleurs and Pence (1978). The Milky Way is generally agreed to be smaller and fainter than M31, so it would not be useful for the limit calculations. Also, it is generally accepted that the diameters and magnitudes of M31 and M33 are more accurately known than the diameter and magnitude of the Milky Way.

CHAPTER 2

EQUATIONS

A lower limit to the distance modulus of the Virgo cluster can be calculated by assuming that M31, the largest, brightest spiral in the Local Group, has the same linear diameter and absolute magnitude as the largest, brightest spirals in the Virgo cluster. An upper limit to the distance modulus can be calculated by assuming that M33, the smallest, faintest spiral in the Local Group, has the same linear diameter and absolute magnitude as the smallest, faintest spirals in Virgo.

Formulas for the distance moduli can be derived from the triangles in Figure 1. The derivations of these formulas rely heavily on the system of astronomical magnitudes, which is introduced in Appendix A. This introduction should allow readers with a basic knowledge of mathematics to follow the derivations. The Local Group galaxy in the upper half of the figure has a radius r_{LG} and is at a distance D_{LG}, both in parsecs. It is observed to have an angular diameter, θ_{LG},

$$\theta_{LG} = 2\,\phi_{LG} = 2\,\arctan(r_{LG}/D_{LG}).$$

Similarly, the distant cluster member in the lower half of the figure has radius r_c and distance D_c, again in

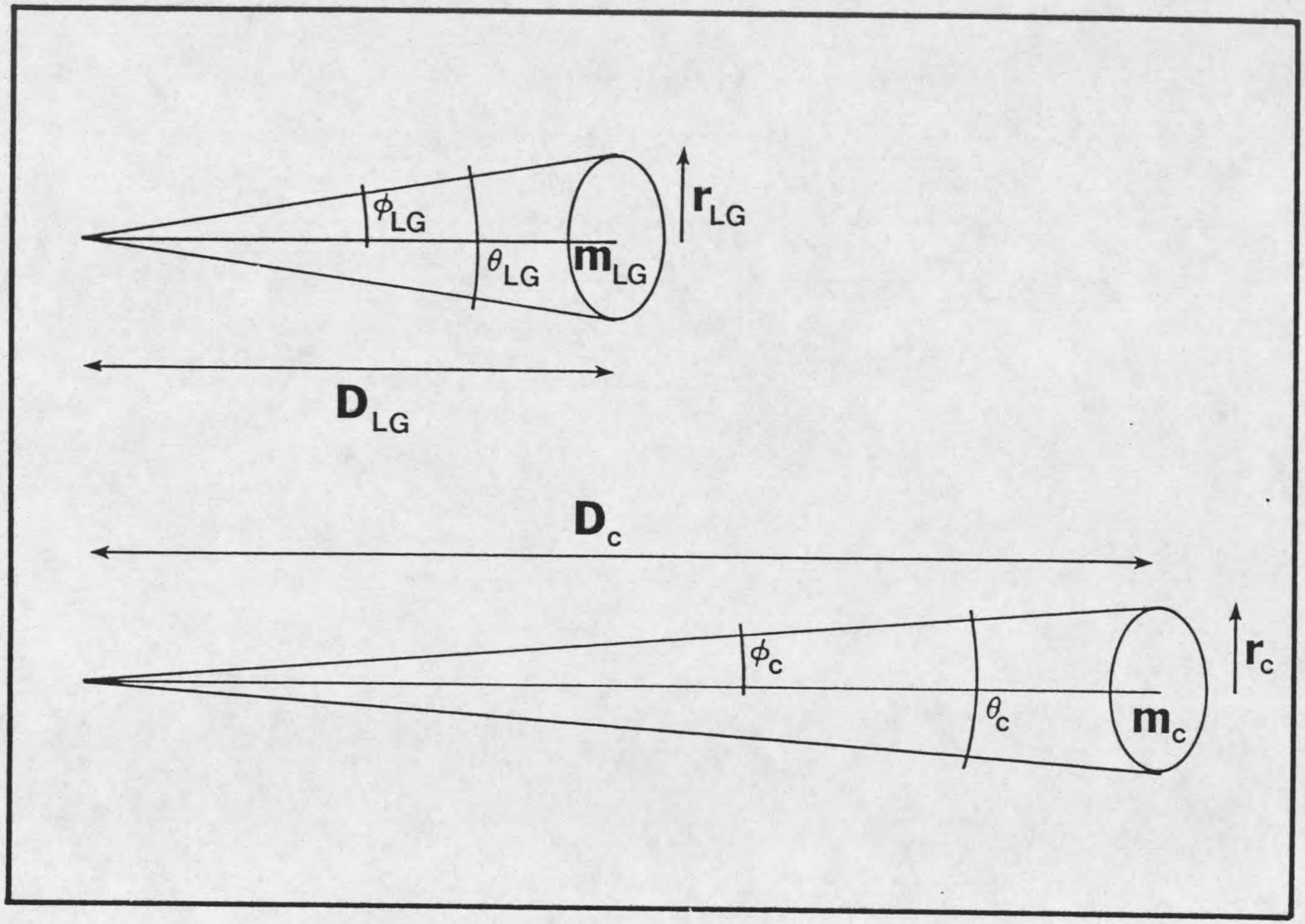

Figure 1. Thin triangles for deriving equations (1) and (2).

parsecs, so it is observed to have an angular diameter

$\theta_c = 2\ \phi_c = 2\ \arctan(r_c/D_c)$.

The distance modulus of the cluster galaxy, and thus the cluster, is

$\mu_c = 5\ \log(D_c/10) = 5\ \log(r_c/10\ \tan\phi_c)$.

We assume the Local Group member and the distant cluster member have the same intrinsic size, so $r_c = r_{LG}$. Then

$\mu_c = 5\ \log(r_{LG}/10\ \tan\phi_c) = 5\ \log r_{LG} - 5\ \log(\tan\phi_c) - 5$

but

$r_{LG} = D_{LG}\tan\phi_{LG}$

so

$\mu_c = 5\ \log D_{LG} + 5\ \log(\tan\phi_{LG}) - 5\ \log(\tan\phi_c) - 5$.

Substitute

$5\ \log D_{LG} = \mu_{LG} + 5$

so

$\mu_c = \mu_{LG} + 5\ \log(\tan\phi_{LG}) - 5\ \log(\tan\phi_c)$.

For Local Group galaxies $\phi_{LG} < 2^o = 0.035$ rad, and making the approximation $\tan\phi_{LG} = \phi_{LG}$ introduces an error in μ_c of no more than 0.0001 magnitude, certainly small enough to neglect. For Virgo cluster galaxies, the largest distant galaxies considered in this work,

$\phi_c < 5$ arc minutes = 0.00145 rad.

Making the approximation $\tan\phi_c = \phi_c$ introduces an error in μ_c of no more than 10^{-8} magnitude, again negligible. The observed quantity is the angular diameter, θ, not the angular radius, ϕ, but

$$\log \theta_{LG} - \log \theta_c = \log(2\phi_{LG}) - \log(2\phi_c)$$
$$= \log \phi_{LG} - \log \phi_c$$

so

$$\mu_c = \mu_{LG} + 5\ (\log \theta_{LG} - \log \theta_c). \quad (1)$$

In this work the largest spiral in the Local Group, M31, will be compared with the largest spirals in distant clusters. Clusters with many members should have many large members, so it is more likely that the largest is intrinsically larger than M31. Equation (1) was derived under the assumption that the intrinsic sizes are the same. If the cluster galaxy is in fact larger, then $r_c > r_{LG}$, so θ_c in equation (1) is too big, so μ_c is too small. Thus, equation (1) gives a lower limit to the distance modulus of the cluster, and, because H is proportional to $\exp(-\mu/5)$, an upper limit to Hubble's constant. Similarly, in this work the smallest spiral in the Local Group, M33, will be compared with the smallest spirals in distant clusters. Again, as clusters have more members they are expected to have more small members, so it is likely $r_c < r_{LG}$. In this case the value of θ_c in equation (1) is too small, so μ_c is too large, resulting in an upper limit to μ_c and a lower limit to Hubble's constant.

Figure 1 also shows the observed magnitudes of the galaxies, m_{LG} and m_c. By definition

$$\mu_c = m_c - M_c.$$

Assume the two galaxies have equal absolute magnitudes (equal intrinsic brightnesses) so $M_C = M_{LG}$, and $\mu_C = m_C - M_{LG}$. From observations of m_{LG} and μ_{LG} calculate

$$M_{LG} = m_{LG} - \mu_{LG}$$

so

$$\mu_C = m_C - (m_{LG} - \mu_{LG}). \qquad (2)$$

Again, as clusters have more members they are expected to have more bright members, and it becomes more likely that the brightest are intrinsically brighter than M31. This means m_C is too small for the assumption imposed in deriving equation (2), so again μ_C is too small, resulting in a lower limit to the distance scale and an upper limit to Hubble's constant. Similarly, the more members the more likely it is that the faintest is fainter than M33, so m_C is too large for the assumptions of equation (2), giving an upper limit to μ_C and a lower limit to H.

So that future adjustments in the Local Group distance moduli may be easily included in the calculations, the final results in this paper will be given as limits to the distance modulus of the cluster. The limits to the distance modulus may be used to find limits to Hubble's constant, H, by

$$H = V \text{ dex}(5 - \mu/5) \qquad (3)$$

where dex is the base-ten exponential function, and V is the radial velocity of the cluster. If V has units of kilometers per second then H has units of km/(sec*Mpc).

CHAPTER 3

INPUT DATA

The distance of the Virgo cluster has been calculated many times, but in every case only one of the many systems of magnitudes, diameters, radial velocities, and Local Group properties has been chosen. This has resulted in a wide range of calculated values of the Virgo distance, and the result depends on the data system. To avoid this problem in the present work, data from all the important systems will be gathered and used in the calculations of the limits to the distance modulus. Gathering the data has been the most ambitious part of this thesis.

Input data needed to carry out the calculations of the distance moduli and H are the distance moduli of the Local Group galaxies, M31 and M33; angular diameters of M31, M33, and distant cluster galaxies; apparent magnitudes of M31, M33, and distant galaxies; and the radial velocities of the distant clusters. The Virgo cluster will be the primary cluster for this work.

Distance Moduli of M31 and M33

The distance moduli of M31 and M33 were reviewed by van den Bergh (1977) and Hodge (1981), but new publications by Sandage and Tammann (1981) and Sandage (1983) require that the values be reexamined and that their important differences be noted. There are three commonly used sets of moduli, those of van den Bergh (1977), de Vaucouleurs (1978), and Sandage and Tammann (1974a). Other authors have adopted these values and often applied various corrections. The situation is summarized in Table 1, which includes the new moduli of Sandage and Tammann (1981) and Sandage (1983). The moduli calculated by van den Bergh and by de Vaucouleurs rely on several distance indicators, so they should be relatively insensitive to changes in the Hyades distance modulus or Cepheid calibrations. The moduli of Sandage and of Sandage and Tammann rely on Cepheids alone, so they may change with the Hyades modulus or Cepheid recalibration. Van den Bergh (1977) argues that allowing for the high metal abundance of the Hyades will reduce the distance modulus determined from Cepheids, offsetting the increase due to the revised Hyades modulus. Table 1 contains two distance moduli for each galaxy from Sandage and Tammann (1974a) and Sandage and Tammann (1981) (A Revised Shapley-Ames Catalog of Galaxies, hereafter the RSA). The first is from Sandage and Tammann (1974a) and is based on a Hyades distance modulus of 3.03, the second is from the RSA, and is calculated from the first by adding 0.20 due

Table 1. Distance moduli of Local Group galaxies M31 and M33.

Reference	M31	M33	Notes
vdB	24.02	24.06	
dV	24.07 ± 0.16	24.30 ± 0.20	
S+T	24.12	24.56	a
	24.32	24.76	b
S	---	24.23	c

References: vdB = van den Bergh (1972)
dV = de Vaucouleurs (1978)
S+T = Sandage and Tammann (1981)
S = Sandage (1983)

Notes: a. Hyades modulus = 3.03
b. Hyades modulus = 3.23
c. Hyades modulus = 3.24

to the revision of the Hyades modulus to 3.23. The distance modulus of M33 from Sandage (1983) is a redetermination using old observations of the Cepheids, but new observations of the standard stars. This new modulus supersedes the previous ones calculated by Sandage and Tammann. It seems to be based on a Hyades modulus of 3.24.

The distance moduli adopted for the present calculation are 24.10 ± 0.12 for M31, calculated by giving half weight to the two values from the RSA, and 24.20 ± 0.07 for M33, calculated by giving the values of van den Bergh (1977), de Vaucouleurs (1978), and Sandage (1983) equal weight, but neglecting the out-of-date values in the RSA. Only de Vaucouleurs gives estimates of errors in the distance moduli, so the standard deviations adopted here were calculated from the values themselves. The calculated standard deviations are consistent with the value which would result if the other determinations had the same errors as those of de Vaucouleurs.

Systems of Angular Diameters

The angular diameters of the Local Group and Virgo cluster galaxies from all the common systems have not been gathered in one list before, even though they are the standard reference spirals for extragalactic distance scale calculations. The author has searched the well-known catalogs, as well as the obscure papers, to make the list in this thesis reasonably complete. It is expected that the final list of corrected angular diameters will be useful for calculations by other authors.

Isophotal angular diameters will be used for the calculations in this paper. Isophotal diameters have been chosen because they are the most commonly tabulated diameter, and because in Euclidean space the diameter at a given isophote, usually expressed in magnitudes per square arcsecond, is fixed on the galaxy. This is easily shown by the following thought experiment. Suppose an ideal "test galaxy" is available and can be placed at various distances from the Milky Way. The galaxy is placed at distance D and observed at many locations along a diameter, using a square diaphragm of one arc second on a side, until the isophote at 25 magnitudes persquare-arc-second is found. The test galaxy is then moved to a distance 2D and observed again. In Euclidean space when the distance to a galaxy is doubled the flux from the galaxy is reduced by a factor of four, but the area on the galaxy included in the diaphragm is increased by a factor of four. The flux received through the diaphragm remains constant, and so does the calculated magnitude. Thus, the magnitude-per-square-arc-second is independent of the distance for all points on the galaxy. This means the diameter of a given isophote is a simple, reliable distance indicator in Euclidean space. In other spaces the relation between diameter and distance is not so simple (Sandage 1961).

Angular diameters measured in blue light are the most common, because blue-sensitive photographic emulsions have long been available. They are the least suitable diameters for the calculations in this paper because blue light is strongly absorbed in interstellar space, and because the blue light emitted by a distant galaxy is strongly dependent on its star-formation history, which is largely unknown. Red light is more suitable because it suffers less from absorption and is less dependent on the history of the galaxy, but until recently little work has been done in the red. In order to provide a reasonable amount of data for the calculations in this paper, two systems of blue isophotal diameters will be used, the system of Holmberg (1958) and the system of de Vaucouleurs, de Vaucouleurs, and Corwin (1976) (hereafter the RC2). Holmberg's catalog specifies the diameter in arc minutes of the 26.5 magnitude-per-square-arc-second isophote in the blue photographic system, which is equivalent to the 26.6 magnitude-per-square-arc-second isophote in the B band of the UBV system (Heidmann, Heidmann, and de Vaucouleurs 1972). The diameters in the RC2 are given as the base ten log of the diameter expressed in tenths of arc minutes measured at the 25.0 magnitude-per-square-arc-second isophote in the B band of the UBV system, so when expressed in the same units the RC2 diameters are uniformly smaller than the Holmberg diameters. The diameters in the RC2 are mostly mathematically transformed values from some other system; in particular the blue diameters of Nilson (1973) are crucial to the RC2 system. The Nilson diameters themselves will not be presented here because all of the necessary values have been included in the RC2.

Systems of Magnitudes

As in the case of diameters, the magnitudes of the Local Group and Virgo cluster spirals in the several observational systems have not before been gathered into one list. This is surprising because of the important role these galaxies play in defining the extragalactic distance scale. It is expected that the final list of corrected magnitudes in this thesis will be useful for calculations by other researchers.

Several types of magnitudes can be used in calculating the distances to galaxies. Two types will be used in this paper, isophotal magnitudes and total magnitudes. Isophotal magnitudes are found by adding all the light within a given isophote. In Euclidean space the isophote is fixed on the galaxy, so the isophotal magnitude can be used as a distance indicator. Total magnitudes are found by extrapolating the galaxy's brightness profile to zero flux, then adding all the light within the extrapolated profile. The total magnitude is clearly a good distance indicator, and is, perhaps, easier to understand than the isophotal magnitude.

For the calculations in this paper two systems of magnitudes will be used, the isophotal magnitudes in the blue photographic system from Holmberg (1958), and the total blue magnitudes in the B band of the UBV system from the RC2. The Holmberg magnitudes are measured at the 26.5 magnitude-per-square-arc-second isophote in the old blue photographic system.

Again, it is often the case that the RC2 magnitudes are transformed from other systems, so the RC2 is not intended to be independent of previous catalogs. Also, more recent observations are often carefully calibrated to match one of the existing systems of magnitudes or diameters. For instance, the isophotal diameters of Peterson, Strom, and Strom (1979) have been calibrated to the Holmberg system, and the total blue magnitudes of the RSA and of Kraan-Korteweg (1982) are in the B_T system of the RC2.

The Radial Velocity of the Virgo Cluster

Once the limits to the Virgo distance modulus have been calculated they may be used to calculate limits to Hubble's constant, but a value of the Virgo velocity is required. Again, despite many studies of the Virgo cluster, no author has gathered the radial velocity determinations into one list before. The compilation here will point out a major difference between the distance scale calculations of Sandage and coworkers and those of de Vaucouleurs and coworkers.

The possibility that spiral galaxies in the Virgo cluster have an average velocity about 400 km/s greater than elliptical galaxies was raised by de Vaucouleurs (1961) and by de Vaucouleurs and de Vaucouleurs (1963). This has been the crucial issue of the last twenty years in studying the overall velocity of the Virgo cluster. Just as this controversy was warming up, a discovery by Roberts (1975) added an extra difficulty. His comparison of 21-cm radial velocities with radial velocities determined from optical spectra showed that for the velocity range $1200 \leq V \leq 2400$ km/s the velocities determined from optical spectra in the blue were high by about 100 km/s. This has been reconfirmed by Bottinelli and Gouguenheim (1976) and by Lewis (1975). The explanation by Roberts (1975) is that the H and K lines of calcium were used to determine the velocities from blue optical spectra, and in this velocity range the lines from the galaxy were blending with night sky lines, causing the error. A correction, usually called the Roberts correction, can by applied to remove the error. Such a correction should be more applicable to ellipticals than spirals (Roberts 1975, Lewis 1974).

Tammann (1972) reexamined the question of Virgo velocities, using 122 galaxies. A Roberts correction of −100 km/s was applied to galaxies in the velocity range $1200 \leq V \leq 2350$ km/s, and a correction of −50 km/s to galaxies in the range $2350 \leq V \leq 2450$ km/s. When the correction was applied to spirals only, Tammann found the average velocity of the cluster to be 1141 ± 60 km/s. When the Roberts correction was applied to all galaxies he found

$$\langle V_0 \rangle_E = 982 \pm 81 \text{ km/s}$$

for the ellipticals, and a difference in the mean velocities of ellipticals and spirals

$\langle V_0 \rangle_E - \langle V_0 \rangle_S = -233 \pm 181$ km/s

which he concluded was not significant.

It was pointed out by de Vaucouleurs and de Vaucouleurs (1973) that the Virgo region contains many subclusters, and a standard definition of the Virgo cluster would be necessary in order to compare calculations. They limited their discussion to the Virgo I cluster and considered its E, S, and S' clouds, and applied a Roberts correction to spirals only, pointing out that this could only reduce the discrepancy between the spirals and ellipticals. Using some new velocity data they found $\langle V_0 \rangle_E = 1000 \pm 60$ km/s for 25 ellipticals and $\langle V_0 \rangle_S = 1350 \pm 150$ km/s for 26 spirals.

The issue is reconsidered by Sandage and Tammann (1976a), limiting discussion to a circle of 6° radius centered on $12^h\ 35^m$, $+13^\circ\ 06'$ (1950), nearly the same region studied by de Vaucouleurs and de Vaucouleurs (1973), although no detailed list of the individual galaxies was given, so the two samples cannot easily by compared. Sandage and Tammann used a sample complete to the limit of the Shapley-Ames catalog, plus a few fainter galaxies. No Roberts correction was applied. They found

$\langle V_0 \rangle_E = 1079 \pm 79$ km/s

for 50 E and S0 galaxies, and

$\langle V_0 \rangle_S = 1105 \pm 120$ km/s

for 47 spirals. Their mean for all 109 Virgo galaxies with velocities is 1066 ± 68 km/s, and the mean of the same sample with 7 Sm and Im galaxies excluded is 1100 ± 68 km/s.

New calculations by Sulentic (1977, 1980) included new redshifts for 23 galaxies and a sample complete to $m_{pg} = 13.0$ in the circle of 6^{o} radius centered on $12^{h}\ 25^{m}$, $+13^{o}\ 06'$ (1950). No Roberts correction was used, but radio and optical data are averaged for each galaxy, reducing the need for such a correction. He found

$\langle V_0 \rangle_E = 1088 \pm 76$ km/s

for 60 ellipticals, and

$\langle V_0 \rangle_S = 1029 \pm 73$ km/s

for 95 spirals, but the velocity averages for spirals depend strongly on Hubble type, with means 956 ± 143 km/s for 28 Sa-Sb galaxies and 1437 ± 124 km/s for 24 Sbc-Scd galaxies. Sulentic concluded that the late-type spirals do have a larger mean radial velocity than other types.

A calculation by Kraan-Korteweg (1982), using 160 galaxies with $B \leq 14.00$ within 6^{o} of M87 gave a mean velocity of 967 ± 33 km/s with only 12 km/s difference between spirals and ellipticals. No Roberts correction was applied.

Further calculations by de Vaucouleurs (1982b) yielded

$\langle V_0 \rangle_S = 1165 \pm 133$ km/s

for 37 spirals of all types in the S cloud. No Roberts correction was applied, no calculations with ellipticals were included, and the mean velocities of spirals were not recalculated by Hubble type. Still, de Vaucouleurs maintained that a systematic velocity difference between ellipticals and spirals does exist.

Several efforts have been made to explain why such a systematic difference might exist. Originally de Vaucouleurs (1961) and de Vaucouleurs and de Vaucouleurs (1973) proposed the difference was due to two clusters at different distances seen in projection. This idea has been discounted by several authors, notably Kowal (1969) and Sulentic (1977), but the issue has been at least partially reopened by de Vaucouleurs (1982b). Non-velocity redshifts have been proposed by Arp (1968), de Vaucouleurs and de Vaucouleurs(1972), Jaakkola (1971), and Jaakkola and Moles (1976). The dynamics of the cluster have been suggested as a possible cause by Fairall (1978), Moles and Nottale (1981), and de Vaucouleurs (1982). Inclination effects on galaxy velocities have been studied by Ftaclas et al. (1981), and projection effects within the cluster by Capelato et al. (1983). Sulentic (1977) and Moles and Nottale (1981) have remarked on the correlation between spiral galaxy redshift and radio emission.

The literature holds still more on the Virgo cluster. The Center for Astrophysics catalog of galaxy clusters

(Geller and Huchra 1983) lists 248 Virgo cluster members with a mean radial velocity of 1495 km/s, which includes a correction of 300 km/s for the motion of the Local Group toward Virgo. No segregation of elliptical and spiral galaxies is made, and the list includes both the Virgo I and Virgo II clusters, so it is not directly comparable with the other studies.

Finally, a list of the Virgo velocities used in the most quoted calculations of Hubble's constant might be of use. Sandage and Tammann (1976b) use 1100 ± 68 km/s from Sandage and Tammann (1976a). Tully and Fisher (1977) use 1111 ± 75 km/s from Sandage and Tammann (1974b), which includes prepublication results from Sandage and Tammann (1976a). De Vaucouleurs and Bollinger (1979) use 1402 km/s for 47 spirals in their region C+, which includes Virgo spirals and others, but 1322 km/s for 26 galaxies in region C–, which excludes the Virgo galaxies. This implies 1501 km/s for the Virgo spirals. Mould, Aaronson, and Huchra (1980) use their own determination of 1019 ± 51 km/s.

Some of the differences in velocity may be due to the type of velocity used in the calculations. Work before 1978 is probably based on galactocentric velocities, that is, velocities corrected for the motion of the Sun about the center of the Milky Way. The RC2 gives galactocentric velocities. After 1978 the work of Sandage and Tammann relies on velocities corrected to the centroid of the Local Group. The RSA gives such velocities. For the Virgo galaxies the galactocentric velocities are larger by 40 km/s.

After this review it is evident that the radial velocity of the Virgo spirals used by Sandage and Tammann in their distance scale calculations is 400 km/s smaller than the velocity used by de Vaucouleurs and coworkers. This accounts for half of the difference in their values of Hubble's constant in the direction of Virgo.

The velocity of the Virgo spirals seems to remain an open issue. The mean velocity of the cluster is 1100 ± 100 km/s in round numbers, and there is reason to believe the velocity of the late-type spirals in the Virgo I cluster fall within 1500 ± 100 km/s. Because no clear-cut answer exists both values will be kept for the calculations. These values have not been calculated by taking means of the values in the literature because those values are certainly not independent. Rather, these values are "best guesses" and the errors only representative.

CHAPTER 4

CORRECTIONS FOR MILKY WAY ABSORPTION

Introduction to Data Corrections

Despite the large number of papers on Milky Way absorption, little has been done in the last few years to review the work on correction of galaxy magnitudes and diameters. The paper of Holmberg (1974) will be used as a starting point, but to bring the field up to date important work on galaxy counts, colors of objects, and radio correlations will be added. Such a review, particularly of work at high galactic latitudes, is overdue.

All galaxies are observed through our own Milky Way because the sun is located in the disk of our Galaxy. This means that the interstellar dust and gas within the Milky Way absorb some light from distant galaxies. For the calculations in this paper the absorption has two important consequences; it makes galaxies look fainter than they would otherwise look, so it makes the isophotes fainter and the angular diameter is smaller than it would otherwise be. The amount of absorption depends upon how much of the Milky Way we must look through to see the galaxy. The effect is greatest when looking through the plane of the Milky Way and least when looking toward the galactic poles.

Spiral galaxies are also observed at various angles of inclination, i, relative to our line of sight. If it is assumed that a galaxy is an ellipsoid of revolution filled with luminous matter, then as a galaxy is tipped from face-on to edge-on the angular diameter of a given isophote is expected to increase because the optical path contributing to the light increases. Actually, the situation is not so simple, because the ellipsoid contains interstellar dust and gas (obscuring matter), concentrated toward the plane of the galaxy, along with luminous matter. This means that as the galaxy is tipped from face-on to edge-on more and more dust is likely to hide our view of what is inside the galaxy in exactly the same way interstellar dust in the disk of the Milky Way hides our view of objects outside our own galaxy.

To compare the intrinsic sizes and brightnesses of spiral galaxies, as in distance-scale calculations, corrections must be made for Milky Way absorption and inclination. These corrections are undoubtedly the most difficult part of the present work. There is disagreement over what form of correction to apply, if, indeed, any should be applied at all. The author would like to recommend that readers who are not required to read this thesis, or do not wish to understand how the corrections are made and how the several systems differ, might content themselves by looking at the summary of adopted corrections in Chapter 6.

The data and corrections are so varied that a review of correction schemes is difficult to organize. There is no consistent set of symbols for naming the physical variables involved, so often one symbol stands for two very different quantities. To render the material approachable, the corrections for Milky Way absorption will be reviewed in this chapter, and in Chapter 5 each correction scheme for the other effects will be considered. A review in Chapter 6 will present all the correction systems for all the effects in one consistent set of notation.

Corrections to magnitudes are of the general form

$$m_0 = m - A_B - A(i) - KV$$

where m_0 is the corrected magnitude, m the raw magnitude, A_B the correction for Milky Way absorption (usually a simple function of galactic latitude, b), A(i) the correction for the inclination of the galaxy being studied, and K the cosmological K-correction for the effect of radial velocity, V. Corrections to angular diameters are similar, however there is no generally-recognized set of symbols for the corrections. For galaxies in the Virgo cluster the K-corrections listed in the RC2 and the Holmberg catalog are always less than 0.015 magnitude, certainly less than the error in the raw magnitudes, so the corrections may be ignored.

Authors agree that both magnitudes and diameters must be corrected for absorption within the Milky Way, but the form and size of the corrections are in dispute, particularly near the galactic poles. Settling the disagreement would involve solving two problems: first, determining the form and slope of the Galactic absorption function; second, determining the polar absorption.

The Form and Slope of the Galactic Absorption Function

There are two common methods for determining the absorption of the Milky Way. One can count the observed distribution of extragalactic objects under the assumption that they are uniformly distributed in space, so the variation of counts with galactic latitude gives the galactic absorption. This has classically been done with galaxies (Hubble 1934, Shane and Wirtanen 1967) and more recently with clusters of galaxies (Holmberg 1974). It is also possible to observe the colors of extragalactic objects--the intrinsic colors need not be known, but the intrinsic color of a given class of objects is taken to be constant. Variation with galactic latitude of the average observed color of the class gives the absorption through an assumed relation between total and selective absorption. There is also the unique method of Rubin et al. (1976) which will be mentioned briefly here and described in more detail in Chapter 5. All of these methods assume the intergalactic absorption is negligible compared with the Galactic absorption.

Results from Counts of Galaxies and Clusters of Galaxies

Much effort has been centered on determining the Milky Way absorption from galaxy counts. First, assume that faint galaxies are distributed uniformly in space, and that the number of galaxies per square degree brighter than apparent magnitude m depends upon m as dex(0.6 m). Then, comparing a reference region of low obscuration with an obscured region in a static, non-evolving Euclidean universe,

$$\log N'(m) = \log N(m) - 0.6\ A$$

where A is the difference in obscuration found from the Galactic absorption function, N(m) is the number of galaxies per square degree brighter than m in the reference region, and N'(m) is the number per square degree brighter than m in the obscured region. The reference region is usually taken to be one of the galactic poles, $|b| = 90^{o}$, so A relates the absorption of any field to the absorption at the pole. If the Milky Way absorbing layer is an infinite, plane-parallel sheet, then it is well known that the galactic absorption function will be a cosecant function,

$A = A_0 \csc|b|$

where b is the galactic latitude and A_0 is the polar absorption, so

$\log N'(m) = \log N(m) - 0.6\, A_0 \csc|b|$

(Knapp and Kerr 1974). Thus, the galactic absorption function is assumed to have the functional form $A_0 \csc|b|$, and the slope, A_0, is determined from the counts N'(m) by fitting them to a function

$\log N'(m) = \alpha - \beta \csc|b|$

where $A_0 = \beta/0.6$. The factor of 0.6 decreases when galaxy evolution and redshift are taken into account (Shane and Wirtanen 1967, Noonan 1971, Knapp and Kerr 1974). It must be remembered that the slope of the relation, A_0, is also the polar absorption, as can be seen by letting $b = \pm 90^{\circ}$.

The necessity for determining the absorption function was stated in modern form and reviewed by Hinks (1911). The present disagreement over the size ot the correction dates back to the 1930's, if not earlier. Hubble (1934) found in a pioneering analysis of galaxy counts that the absorption function in the blue photographic band is not significantly different from csc|b| all the way to the poles, where A = 0.25 magnitude. Hubble and others wrote this as a pole-to-pole absorption of 0.50 magnitude. This result was substantiated by the galaxy count work of Mineur (1938), who also pointed out that galaxies of bright apparent magnitude are not distributed uniformly. Oort (1938) studied the absorption of light from galactic OB stars and found a polar absorption of 0.12 magnitude, or, as he expressed it, a pole-to-pole absorption of 0.25 magnitude, half of Hubble's value. Oort attributed this difference to absorbing clouds beyond the OB stars but still within the Milky Way, in what we would now call the Galaxy's halo. The existence of such clouds was substantiated by the spectra of galaxies near the north galactic pole (Mayall 1934) which were known to show interstellar calcium lines. Despite these disagreements over the value of the absorption toward the poles, by 1940 it seemed to be well established that the Galactic absorption function is linear in csc$|b|$, is nearly the same in the northern and southern galactic hemispheres, and is largely independent of galactic longitude, λ, for $|b| > 15^o$, but below 15^o the absorption is strong and patchy, with significant dependence on λ in the sense that there is more absorption toward the Galactic center than toward the anticenter.

More recently, the review and compilation of data by Holmberg (1974) brought the disagreement up to date. A summary and updating of the situation is given here.

The counting of galaxies is a slow, tedious business, so it is rarely done. The counts most often analyzed are those of Hubble (1934) and Shane and Wirtanen (1967).

Authors interested in the galactic absorption function usually reanalyze one of these sets of counts. De Vaucouleurs and Buta (1983) have reviewed this work, and show that all of the counts obey the csc|b| law all the way to the poles, but values of A_0 differ greatly. Hubble (1934) found $A_0 = 0.25$ magnitude, and a reanalysis of Hubble's counts by de Vaucouleurs and Malik (1969), including longitude dependence and a reexamination of low-latitude fields, gave $A_0 = 0.20$ magnitude, but the functional form is more elaborate, involving csc|b| multiplied by other terms involving sin λ, cos λ, and cos 3λ, where λ is galactic longitude. This forms the basis for the RC2 correction for Milky Way absorption.

Shane and Wirtanen (1967) found a csc|b| law with $A_0 = 0.51$ magnitude, double Hubble's value. A reanalysis by Heiles (1976) gave $A_0 = 0.25$, and another by Seldner et al. (1977) gave $A_0 = 0.59$. All of these analyses included terms for extinction within the Earth's atmosphere.

The differences among these analyses of counts are smaller than they appear, for they are based on different assumptions. In general

$\log N'(m) = \alpha - \beta \csc|b|$

and $\beta = \gamma A$, where $\gamma = 0.6$ for a static, Euclidean universe. Hubble finds $\beta = 0.15$, and uses $\gamma = 0.6$, so $A_0 = 0.25$ magnitude, but de Vaucouleurs and Malik (1969) find $\beta = 0.205 \pm 0.007$ from Hubble's counts, and assume $\gamma = 0.44$ from Shane (1968), so $A_0 = 0.47 \pm 0.02$ magnitude. This value is then revised downward on the basis of two arguments. First, if $A_0 = A_B = 0.5$ magnitude, and $E(B-V) = 0.05$ for galaxies near the north galactic pole (Holmberg 1958, de Vaucouleurs 1961) then $R+1 = A_B/E(B-V) \sim 10$, much larger than the accepted value of 4.0. Second, the calculation of E(B-V) requires a sample of low-latitude galaxies. Such a sample is probably biased in the sense that known low-latitude objects have brighter than average magnitudes and and surface magnitudes, or are found in regions of low obscuration. This results in a value of E(B-V) which is too low. It is proposed that the correct value of A_0 results from the requirement $R+1 = 4.0$, giving $A_0 = 0.20$ magnitude.

Shane and Wirtanen (1967) find $\beta = 0.242$, and use $\gamma = 0.47$ due to theoretical redshift and evolution corrections, so $A_0 = 0.51$ magnitude. Seldner et al. (1977) do not specify their values of β or γ, but presumably they adopt $\gamma = 0.47$ from Shane and Wirtanen, so they calculate $A_0 = 0.59$. Heiles (1976) calculates $\beta = 0.250$ and determines $\gamma = 1.0$ using two empirical methods, one involving the dependence of galaxy counts on zenith angle and the other involving the assumption that $R = 4.0$. The result is $A_0 = 0.25$ magnitude. Finally, Holmberg (1974) reexamines the Shane-Wirtanen counts and