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
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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 ± 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.

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of the requirements for the degree

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APPROVAL

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David John Westpfahl Jr.

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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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 ± 10 km/(s*Mpc) and 62 ± 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 ± 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

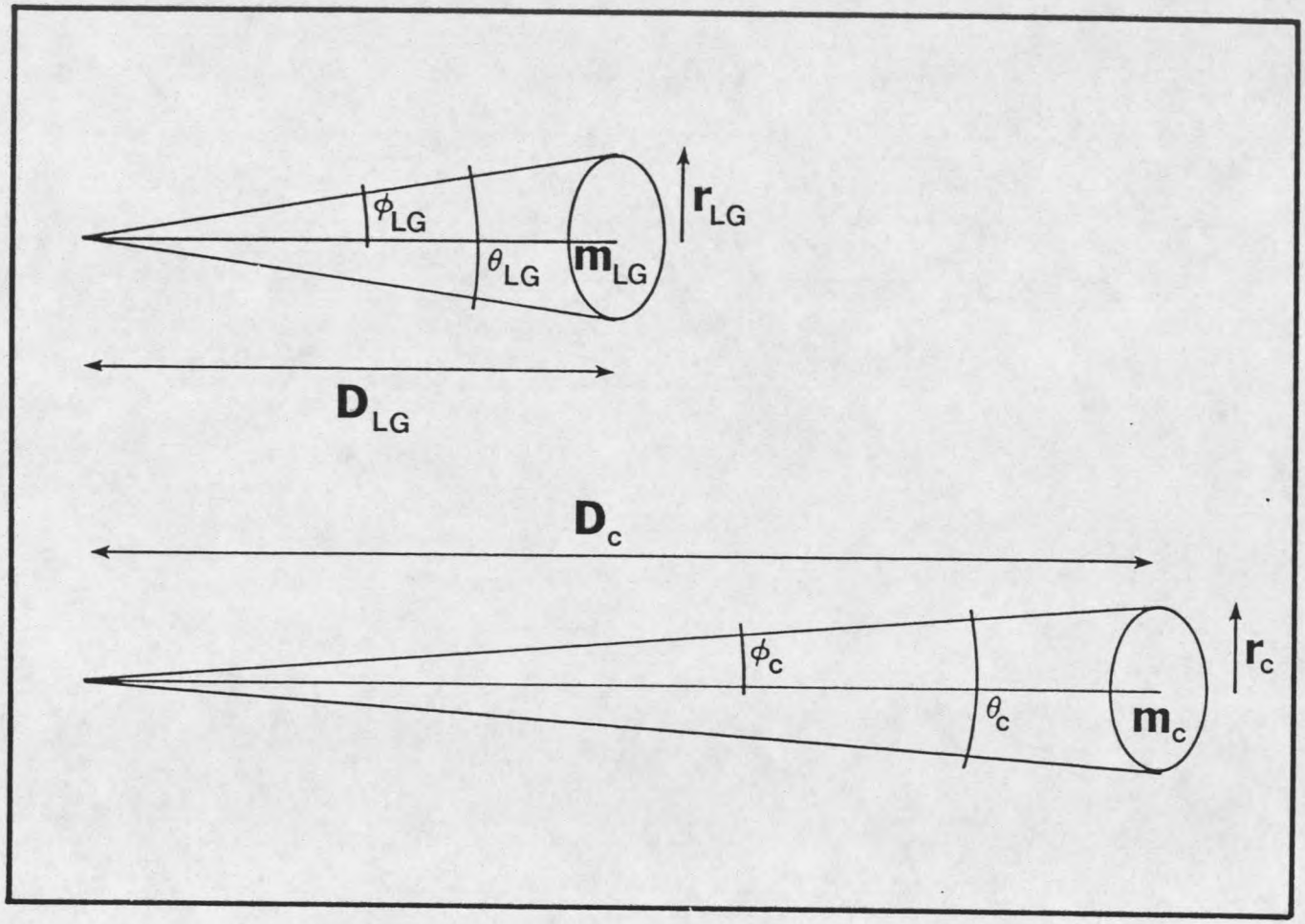


Figure 1. Thin triangles for deriving equations (1) and (2).

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 $\phi_{LG} < 2^\circ = 0.035$ 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

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

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

$\langle V_0 \rangle_E = 982 \pm 81$ 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 $\pm$ 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 $\pm$ 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, $|b| = 90^{\circ}$, 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 $|b| > 15^{\circ}$, but below 15° 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

their corrections, and determines $0.251 < \beta < 0.299$ depending on the corrections applied, but no value of γ is assumed, so no value of A_0 is calculated.

Noonan (1971) and Holmberg (1974) use the cluster lists of Zwicky and collaborators (1961-1968) as a set of counts of individual galaxies, and analyze them. Noonan emphasizes that knowledge of γ is as important as knowledge of β in determining A_0, and use of the Zwicky catalogs with a limiting magnitude of about 15.7 should minimize the errors due to redshift (because few of the redshifts are large). From the galaxy counts Noonan finds $\beta = 0.175 \pm 0.010$, and from theory $\gamma = 0.554 \pm 0.025$, so $A_0 = 0.315 \pm 0.023$ magnitude. Holmberg (1974) applies two analyses, varying in the way the mean N'(m) is found for each zone of galactic latitude. Using

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

Holmberg finds $\beta = 0.180$, but using

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

he finds $\beta = 0.253$. Analyses by other authors are based on $\log \langle N' \rangle$. It is not clear which is the "correct" choice, but both $\log \langle N' \rangle$ and $\langle \log N' \rangle$ are well-represented by cosecant functions. Holmberg does not assume a value of γ, so he is not able to calculate A_0, but his values of β using both formulations are consistent with the values of the other researchers.

Holmberg (1974) develops the idea of using counts of clusters of galaxies to study the distribution of Milky Way absorption. The clusters in the Zwicky catalogs are found to obey a cosecant law all the way to the poles, overall

$\log N = 2.060 - 0.532 \csc|b|$

and although the highest latitude zone includes $|b| > 63^{\circ}$, no evidence for polar absorption is found. There is no simple way to turn this cosecant dependence into a value of A_0--the theory is difficult enough for individual galaxies, let alone clusters. Holmberg includes important analysis of the deviation of the counts from linearity which suggest that the absorbing material is patchy and its distribution follows Poisson's law.

A similar analysis of clusters has been published by de Vaucouleurs and Buta (1983) using the cluster lists of Zwicky plus the list of Abell (1958). The density of clusters in the two catalogs is normalized at $\csc|b| = 1.55$, and the average counts ($\log \langle N \rangle$) are found to agree well. Neither shows evidence for polar windows, both follow the cosecant law.

In summary, both galaxy and cluster counts show the Milky Way absorption follows the cosecant law from $|b| = 15^{\circ}$ to the poles, but β is uncertain. Both types of counts are difficult to turn into absorption values because the theory of how counts of extended objects are

affected by absorption is poorly understood, that is, γ is uncertain. The determination of A_0 from galaxy counts is known to break down because bright galaxies are not distributed uniformly and because galaxies are detected on the basis of their surface brightness, not their integrated magnitude. This means that at low latitudes fewer than the actual number of galaxies of total magnitude m are counted, some because they no longer have enough surface brightness to appear above the plate limit and some because their diameters have been reduced so they are indistinguishable from stars (Knapp and Kerr 1974, Holmberg 1974, de Vaucouleurs and Buta 1983). The result is that the Milky Way absorption is overestimated. All of the galaxy and cluster count analyses show that log N'(m) follows a cosecant law all the way to the poles, implying that the reduction in the counts due to considering surface brightness effects must also follow a cosecant law (Holmberg 1974).

Before this is accepted as the final word, the reanalysis of the Shane-Wirtanen counts by Burstein and Heiles (1978) must be considered. Using the system from Heiles (1976) for correcting the counts, they find the noise in the counts for $\csc|b| \leq 1.16$, that is, $|b| > 60^{\circ}$, is so large that the slope of the counts versus $\csc|b|$ cannot be determined with acceptable accuracy--it cannot be determined if there is any absorption at the north

galactic pole, or even if the counts are roughly linear in csc|b|. The same uncertainties are found in the counts of Zwicky clusters analyzed by Holmberg (1974). On the other hand, reanalysis of the counts by Fesenko (1980) shows that there is considerable correlation between csc|b| and the Shane-Wirtanen counts near the north pole corrected by the method of Kiang (1968), but the correlation is stronger for $50^{\circ} \leq b \leq 60^{\circ}$ than for $60^{\circ} \leq b \leq 90^{\circ}$.

Results from Analysis of Colors of Objects Outside the Absorbing Layer

The form and slope of the Milky Way absorption may also be determined from the change of observed color with galactic latitude of a uniform class of objects known to be outside the Galaxy's absorbing layer. The intrinsic color of the objects need not be known, it may be found as part of the calculation of the latitude dependence of the observed color. The relation between absorption and reddening (also known as the relation of total to selective absorption) may then be applied to find the absorption. Galaxies, RR Lyrae stars, and globular clusters are used in these calculations. This work has been reviewed by Holmberg (1974) and by de Vaucouleurs and Buta (1983), so it is only summarized here.

One of the difficulties in using galaxy magnitudes (or counts to a given apparent magnitude) is that there are few known low-latitude ($|b| < 10^{\circ}$) galaxies, and most

of these are either in regions of low absorption or are intrinsically brighter than average. Such selection effects lead to an underestimate of the slope of the Milky Way absorption. Holmberg (1974) has shown that the size of this effect is greatly reduced by using galaxy colors instead of magnitudes. Using his analysis of the dispersion of individual absorption values, Holmberg finds the variation in color will be underestimated by only 0.004 csc|b| in E(B-V), so he applies this correction to the calculations. Using the m(pg) - m(pv) colors of 174 spiral galaxies, Holmberg (1958) finds:

$$m(pg) - m(pv) = \text{const.} + (0.062 \pm 0.007)\ \csc|b|$$

where the constant depends upon galaxy type. This is converted to the UBV system by a factor of 0.87 (Holmberg 1974), so

$$E(B-V) = (0.054 \pm 0.006)\ \csc|b|$$

or, adding the correction for selection effects,

$$E(B-V) = (0.058 \pm 0.006)\ \csc|b|$$

This may be converted to A_0 by multiplication by R+1. Holmberg (1974) does not assume a value of R+1, although statements in the paper suggest he would favor 4.55, even though 4.0 is the value traditionally adopted. If R+1 = 4.0, A_0 = 0.23 magnitude, if R+1 = 4.55, A_0 = 0.26, both consistent with determinations from galaxy counts.

Holmberg also analyzes the color residuals, a new method for determining the reddening. The result is 0.062 ± 0.016, giving $A_0 = 0.25$ or $A_0 = 0.28$ magnitude for R+1 = 4.0 and 4.55 respectively.

Holmberg reanalyzes the data of Peterson (1970) on the brightest galaxies, usually giant ellipticals, in over 50 clusters and groups. After transformation of the V,r colors to the UBV system and correction for selection effects, $E(B-V) = (0.052 \pm 0.012)\ \csc|b|$ is adopted as a preliminary determination. This gives $A_0 = 0.21$ and 0.24 magnitude for R+1 = 4.0 and 4.55. Peterson's contribution was the recognition that working in the red would minimize redshift corrections.

Sandage (1973) expanded upon Peterson's observations by using UBVr colors and transforming to the UBV system. Motivated by several papers which show the polar reddening to be near zero (see the next section) he assumed A = 0 for $|b| \geq 50^{\circ}$ and fit the colors of galaxies to the unconventional function $\csc|b| - 1$, rather than the conventional $\csc|b|$. This choice must be examined in more detail.

It is well known that if the absorbing layer in the galactic plane has constant density and plane-parallel boundaries then the galactic absorption is

$$A(b) = A_0 \csc|b|$$

where A_0 is the polar absorption. It is also well known

that observations should follow this function only in the mean; in general the galactic absorption is patchy, and stronger toward the galactic center than the anticenter. The linearity of galaxy counts with csc|b| is often cited to support this simple absorption function, but the linearity of the counts (which is not beyond dispute in the galactic poles) only establishes that the absorption has the form

$A(b) = \text{const.} + A \csc|b|$

Noonan (1971) writes this relation as

$A = a' + a(\csc|b| - 1)$

where a' is the polar absorption and a is the slope of the plot of log N'(m) versus csc|b| in a galaxy count study. He remarks that theory says a and a' should be the same, so the absorption function reduces to the simple form

$A(b) = a \csc|b|$

Choosing an absorption function

$A(b) = \text{const.}(\csc|b| - 1)$

requires the assumptions that $a' = 0$ and $a' \neq a$. These assumptions are consistent only if there are polar windows, or at least a north polar window, in the galactic absorbing layer. The possibilities of polar windows or an absorption-free bubble near the sun have been much discussed, even though galaxy counts favor the cosecant law all the way to the poles, strongly refuting the existence of such windows. The model most often cited for

polar windows is that of McClure and Crawford (1971) in which the absorbing layer has a cylindrical hole centered on the Sun. The diameter of the hole is equal to the half-thickness of the absorbing layer, so there are windows above b ~ 60°. The authors present this model as a feasibility argument, or, in the authors's words, a "hypothetical model" to demonstrate one possible reconciliation of polar windows with an absorption function which is nearly indistinguishable from a cosecant function at low and intermediate latitudes. It is not presented as an accurate description of the absorbing layer near the Sun, and adoption of the model would seem to be premature without well-accepted observational evidence. McClure and Crawford find $E(B-V) = 0.00 \pm 0.01$ at the north galactic pole, using DDO photometry of K giants. They also review other determinations of the polar reddening, and although they favor $E(B-V) = 0$, they are not able to dismiss all other determinations. This problem will be discussed in more detail below.

In sum, the model of McClure and Crawford probably was not intended to represent the actual reddening, but only to show how two discordant observations might be reconciled. The evidence for zero reddening at the galactic poles is not beyond dispute, so the assumption of polar windows and the use of $\csc|b| - 1$ for the absorption function may be premature.

In an analysis of the colors of galaxies in the RC2 de Vaucouleurs and Buta (1983) test the RC2 model of Milky Way reddening and absorption by writing

$(B-V)_c = (B-V)_o - E_T(B-V) - K'(T)cz$

where $(B-V)_o$ is the observed integrated asymptotic color index, B_T-V_T, $(B-V)_c$ is the corrected integrated asymptotic color index, $E_T(B-V)$ is the total reddening due to Milky Way absorption and inclination,

$E_T(B-V) = (A_B + \alpha(T) \log R_{25})/(R+1)$

(in this equation $A_B = A_0 \csc|b|$, and the inclination correction, $\alpha(T) \log R_{25}$, will be described in the next chapter) where $K'(T)cz$ is the K-correction for redshift. The mean corrected color, $\langle(B-V)_c\rangle$, is found for each galaxy type, and the deviations from the mean colors are analyzed to test the RC2 absorption model. The absorption is found to follow a cosecant law all the way to the poles, and under the assumption $R = 3.33$ it is found $A_0 = 0.19 \pm 0.02$, consistent with the RC2 model. A similar analysis using U-B colors gives $A_0 = 0.22 \pm 0.04$. These values agree well with the other determinations from galaxy colors, which may be summarized by $0.19 \leq A_0 \leq 0.28$, where some of the uncertainty is due to uncertainty in R.

Similar calculations with RR Lyrae stars and the data of Sturch (1966) and Jones (1973) have been published by Holmberg (1974). Including a correction for selection

effects, Holmberg finds the reddening to be 0.059 ± 0.005 in the northern hemisphere and 0.057 ± 0.011 in the southern, essentially the same. These give A_0 = 0.24 and A_0 = 0.27 magnitude in the north, A_0 = 0.23 and A_0 = 0.26 magnitude in the south for R+1 = 4.0 and 4.55 respectively. Determinations using RR Lyrae stars have been questioned because the composition of the stars may depend on their distance from the plane of the Galaxy. This would introduce a latitude dependence to the observed colors. Holmberg has taken steps to eliminate this dependence.

Finally, Holmberg (1974) reanalyzed the globular cluster data of van den Bergh (1967). It is assumed that the intrinsic color of a globular cluster is a linear function of its integrated spectral type. The observed color then depends on spectral type and galactic latitude. The coefficient of the csc|b| term is found to be 0.047 ± 0.009, so A_0 = 0.19 for R+1 = 4.0 and A_0 = 0.21 for R+1 = 4.55.

In summary, all analyses using observed colors give $0.19 \leq A_0 \leq 0.28$, with some of the disagreement coming from the determination of the coefficient multiplying csc|b| and some coming from the uncertainty in R. These values agree reasonably well with the lowest values from galaxy counts, which fall in the range $0.20 \leq A_0 \leq 0.59$. Holmberg (1974) determines from these analyses that the

mean E(B-V) is 0.054 ± 0.004, from which he infers $A_0 = 0.22$ if R+1 = 4.0, or $A_0 = 0.25$ if R+1 = 4.55. De Vaucouleurs and Buta (1983) give a mean absorption $A_0 = 0.200 \pm 0.018$ and take this to be the proper absorption for a sample of galaxies chosen by apparent magnitude and including the bias toward low-absorption regions for a given b. Thus, they take $A_0 = 0.20$ to be a lower limit to the absorption in an unbiased sample.

Results from Other Methods

Several other methods have been used to determine the Milky Way absorption. Holmberg (1958) and de Vaucouleurs and Buta (1983) use the latitude dependence of surface magnitudes of galaxies. Holmberg finds for $|b| > 20^{\circ}$ that $A_0 = (0.26 \pm 0.07) \csc|b|$ in the blue photographic band. He cautions that the error is large, probably due to the compounding of observational errors in calculating surface magnitudes, the uncertainty in the correction for inclination effects, and the high intrinsic dispersion in surface magnitudes, even among galaxies of a given type. De Vaucouleurs and Buta use mean effective surface brightness in the B band to test the RC2 extinction correction, and reconfirm the functional form, but find a correction to the extinction of 0.04 ± 0.03, which could lower the RC2 correction to 0.16 magnitude in B.

In another determination, de Vaucouleurs and Buta (1983) define a neutral hydrogen index, HI, which is a magnitude measure of the ratio of the integrated 21-cm flux (corrected for self-absorption) to the integrated blue light. A similar unpublished calculation was used in defining the RC2 absorption correction. Because the method is complex only the results are stated here, but a review of the RC2 method is given in the next chapter. The hydrogen index confirms the form of the RC2 correction, but suggests that A was underestimated by the negligible amount 0.01 ± 0.03 magnitude.

Perhaps the most interesting new method has been proposed by Teerikorpi (1981) in which the reddening of radio-detected quasars is used to find A_0. Quasars are excellent objects for absorption studies because they are certainly outside the Milky Way dust layer, are generally agreed to have an isotropic distribution, have small angular extent, and have been chosen on the basis of radio observations (presumably reducing absorption-dependent selection effects similar to those found in galaxy counts). They are difficult to use for reddening determinations because of the large cosmological K-corrections which must be applied to their colors and because nothing is known about the environment of quasars and associated absorbing matter. Nonetheless, Teerikorpi shows quasar colors are a promising new indicator of

galactic reddening and absorption, and presents as a preliminary result $A_0 > 0.25$ magnitude.

Rubin et al. (1976) use their data on Sc galaxies to calculate sequentially a set of corrections which includes a determination of the Milky Way absorption. This set of corrections will be reviewed in the next chapter, so only the results will be given here. A correction of the form A_B (csc|b| - 1) is assumed, so the polar absorption is taken to be zero, and $A_B = A_0$. Using their data for 96 of the 201 ScI galaxies, Rubin et al. find $A_B = 0.15 \pm 0.03$ magnitude. Fesenko (1979) criticizes this value as being artificially low due to the simultaneously applied constraints on radial velocity and apparent magnitude. Using a subset of 107 galaxies from the Rubin et al. list, Fesenko calculates a new set of corrections with the assumption the Milky Way correction is of the form csc|b|. Taking a mean of three calculations using diameters, colors, and absolute magnitudes he determines $A_0 = 0.315 \pm 0.064$ magnitude.

The Polar Reddening and Absorption

In the analysis of galaxy counts the equation

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

is used to determine A_0 from the counts. When $b = \pm 90^{\circ}$, $\csc|b| = 1$, so

$$\log N'(m) = \log N(m) - A_0$$

and it can be seen that A_0 represents the absorption at the poles as well as the slope of the galaxy counts. The studies in blue wavelength bands show $0.20 \leq A_0 \leq 0.60$ magnitude in round numbers. In the analysis of colors of objects outside the Milky Way absorbing layer a similar equation, such as $(B-V)_{obs} = (B-V)_{intrinsic} + E(B-V)\ \csc|b|$ is used to find $E(B-V)$ and $(B-V)_{intrinsic}$. When $b = \pm 90^{o}$ it can be seen that $E(B-V)$ is the polar reddening as well as the slope of the observed color. Studies of galaxies, RR Lyrae stars, and globular clusters give $0.044 \leq E(B-V) \leq 0.062$, consistent with the lower values of A_0 under the assumption $R+1 = 4.0$. These values must be compared with determinations of $E(B-V)$ at the poles from other types of stars for which $(B-V)_{intrinsic}$ is calibrated independently. This is an important difference!

Determinations of the polar reddening using stars of calibrated intrinsic B-V color are reviewed by Holmberg (1974) and by Burstein and Heiles (1982). The overview presented here will be based on those two sources, and is meant to be brief and not exhaustive. Between 1970 and 1982 there were at least thirteen major studies of north and south polar reddening, using B, A, F, G, and K stars in the UBV, uvby , Geneva, and DDO systems, Using independently determined intrinsic colors of the classes of stars involved, all authors have found values for

E(B-V) of 0.057 or less, with seven studies giving E(B-V) < 0.015. Burstein and Heiles (1982) have shown that the relative reddenings in these studies agree very well, but the absolute reddenings differ in a manner easily explained by variations in reddening zero points of the photometry. Differences due to variations in the reddening scale, patchiness of the reddening distribution, and luminosity-dependent color differences have been ruled out.

In order to decide on a most likely value for the polar reddening, Burstein and Heiles consider determinations of interstellar polarization of starlight near the north galactic pole. They conclude from the very low polarization that $E(B-V) \sim 0.01$ at the north pole, and $0.01 \leq E(B-V) \leq 0.02$ at the south pole, but caution that the reddening is patchy everywhere, including the north galactic pole. Assuming $R+1 = 4.0$, this means the colors of stars at the north pole give $A_0 = 4\ E(B-V) = 0.04$ magnitude, much less than the absorption found by other methods, where $A_0 = 0.20$ magnitude was the lower limit. Despite many attempts there is no well-accepted explanation or reconciliation of these differences, which were known early-on by Oort (1938).

Results from Correlations with Radio Observations

Several authors have shown that observations of HI column density correlate well with the standard indicators of absorption--galaxy counts; color changes of galaxies, clusters, and RR Lyrae stars; and polar reddening studies. With enough observations it has been possible to calibrate the amount of reddening or absorption with HI observations, culminating in the list of reddening estimates for several thousand galaxies by Burstein and Heiles (1984).

The difficulties of making such a calibration are well known (Burstein and Heiles 1978, Knapp and Kerr 1974). Errors can arise because the gas-to-dust ratio varies, because the HI line saturates, or because H_2 forms. The results of the calibration depend upon the reddening values adopted; some authors adopt $E(B-V) \sim 0.06$, consistent with $A_0 = 0.25$ from galaxy counts. Until there is agreement on the amount of reddening, the HI method will not meet its potential.

CHAPTER 5

CORRECTIONS TO MAGNITUDES AND DIAMETERS FOR MILKY WAY ABSORPTION AND INCLINATION

The several methods for removing systematic errors from galaxy magnitudes and diameters have never been reviewed. The most thorough treatment to date is a few paragraphs in the catalog of Fisher and Tully (1981). To improve this situation, the correction schemes are gathered for the first time in this chapter.

The data used in calculating limits to the distance scale come from only a few catalogs, so only the correction schemes applicable to those catalogs will be considered. The history of corrections to previous catalogs will not be considered.

Holmberg's Corrections

Holmberg (1958) included determinations of corrections as part of his catalog after noting that it contained enough galaxies to determine the corrections from the raw data themselves. Holmberg began by studying the variation of color index, $C = m(pg) - m(pv)$, where m stands for magnitude, pg for the blue photographic passband, and pv for the visual (yellow) photographic

passband. Comparisons are made within galaxy types Sa, Sb-, Sb+, Sc-, and Sc+, which correspond closely with the familiar Hubble types. Several galaxies with unusual properties are excluded from the analysis, including Virgo cluster members of types Sb+, Sc-, and Sc+, which were found to have unusual colors. The observed color, C, is reduced to the color at the galactic pole, C_0, by the provisional correction $-0.063\ (\csc|B| - 1)$, where B is the old galactic latitude. The use of the old latitude could introduce some systematic error, but the new latitude differs by little from the old for most objects, so the error should not be large. The correction for selective absorption (what we now call the reddening) due to inclination is assumed to be of the form $(1 - b/a)$, where b is the minor axis of the galaxy, a is the major axis, and b/a is the axis ratio. The color index corrected to the galactic pole ($B = 90^{\circ}$) and to face-on ($b/a = 1$) is

$$C_0' = C_0 - \beta(1 - b/a).$$

C_0 and b/a can be found in the catalog, and a least-squares solution for the relation between C_0 and b/a gives the value of β for each type: Sc+, $\beta = +0.049$ magnitude; Sc-, $\beta = 0.136$; Sc+, $\beta = 0.123$; Sb- and Sa, $\beta = 0.251$.

Next, Holmberg uses the same material to solve for the effect of selective galactic absorption (the Milky Way reddening). Let C' be the color index corrected for Milky

Way effects only, so

$C' = C - \beta (1 - b/a)$

As a first approximation, assume

$C' = \bar{C}'_0 + E (\csc|B| - 1)$

where $\bar{C}'_0$ is the mean color index corrected to B = 0 and b/a = 1 for the type under consideration, and E, the color excess (reddening) caused by Milky Way absorption in the direction of the galactic poles, is the same for all types. A least-squares solution gives E = 0.062 ± 0.007 magnitude, consistent with the assumption made previously. An analysis of the residuals shows that the assumption that the galactic absorption function is of the form E (csc|B| - 1) is consistent with the data, but that the lack of data at low latitudes is a problem. Holmberg points out that the value of the polar selective absorption, E = 0.062 ± 0.007 magnitude, is consistent with the value of the polar total absorption determined by Hubble (1934), A_0 = 0.25 magnitude, under the assumption that R+1 = 4.0. Finally, separate analysis of the galaxies in the northern and southern hemispheres suggests that the polar selective absorption is larger in the south by about 0.012 magnitude, consistent with the idea that the Sun is north of the plane of the Milky Way. This difference is assumed to be negligible for the purposes of the catalog.

As a final correction to the color, Holmberg finds the change due to redshift. Assume

$C_0' = p + qV$

where V is the radial velocity. To improve the statistics all galaxies are considered together, even though it is clear the redshift effect must depend on the spectral energy distribution, which depends upon type. The result is $q = 0.018 \pm 0.011$ magnitude per 10^3 km/s.

The intrinsic color of a galaxy may now be found by correcting the raw color, C, for inclination by $\beta\,(1 - b/a)$, for Milky Way absorption by $-E\,(\csc|B| - 1)$, and for redshift by qV. This gives the apparent color reduced to b/a = 1.0 (face-on), to the galactic pole ($B = 0^{\circ}$), and to zero redshift. The galaxy is still observed through the obscuring matter between the Earth and the pole of the Milky Way, so making a further correction of -E gives the color as it would appear to an observer outside the Milky Way.

Holmberg's next step is to determine the total internal absorption in spiral galaxies (that is, the total absorption in the blue photographic band, not the reddening). Holmberg was interested in comparing galaxies using the light from the stars and luminous matter only, so he formulated the calculations to correct for total internal absorption due to inclination and for the absorption which occurs even when the galaxy is already

face-on. With this in mind, he wrote

$A = \Delta A + A_0$

$E = \Delta E + E_0$

where A is the total absorption in the blue photographic band, ΔA is the part of A due to inclination, and A_0 is the absorption when the galaxy is face-on. Similarly, E is the selective absorption (reddening in the pg-pv color index), ΔE is the part of E due to inclination, and E_0 is the reddening when the galaxy is face-on. To determine the magnitude corrections these A's and E's must be found. (These are the same as Holmberg's equations on page 46 of the catalog, except that he gives no names to the face-on terms E_0 and A_0.) Usually either A or E is found, then the equation A/E = R+1 is applied. Holmberg's procedure, however, is to solve for both A and E, then see if a reasonable value of R+1 results. It must be clearly understood that Holmberg's corrections give magnitudes which are face-on and dust-free, because they include the terms A_0 and E_0, while most other corrections give magnitudes which are face-on, but not dust-free.

To study the effect of inclination on magnitudes the angle of inclination, i, must be known, but the axis ratio, b/a, is the observed quantity, not i. If a galaxy is assumed to be an oblate spheroid, then the angle of inclination is related to the observed axis ratio by Hubble's well-known formula, which Holmberg writes as

$\sin^2 i = \{(b/a)^2 - p^2\}/\{1 - p^2\}$

Here p is the intrinsic ratio of smallest to largest axis for the spheroid. This means i = 90° for a face-on galaxy (b/a = 1.0) and i = 0° for an edge-on galaxy. Holmberg assumes, from his previous work, that the mean value of p is 0.20 for all spirals, so i may be found from b/a. For inclinations larger than 25° Holmberg finds i is very weakly dependent on the assumed value of p.

To calculate A Holmberg defines the surface magnitude,

$S_0 = m_0 + 5 \log a$

where S_0 is the surface magnitude corrected to B = 90°; m_0 is the raw magnitude, m, corrected for Milky Way absorption by -0.25 (csc|B| - 1), presumably assumed from the work of Hubble (1934), although Holmberg does not state this; and a is the apparent major diameter in minutes of arc. The surface magnitude should be independent of inclination if the galaxy contains no obscuring matter. If there is obscuring matter, then S_0 will vary with inclination, and the total photographic absorption may be estimated.

To determine the absorption Holmberg excludes from his sample all galaxies likely to have higher than average surface brightness, specifically all galaxies with a < 5.0 arc minutes, all galaxies with |B| < 15°, and members of double systems. The remaining galaxies are separated into

two groups, one comprising Sc+ and Sc-, the other Sb+, Sb-, and Sa.

A plot of S_0 versus b/a for each group (Holmberg's Figure 4) shows that S_0 increases as b/a increases, that is, S_0 increases as a galaxy goes from edge-on to face-on. Holmberg assumes

$$S_0 - S_0' = \Delta A = \alpha \, (\csc i - 1)$$

where S_0' is the mean surface brightness corrected to $B = 0^\circ$ and $i = 90^\circ$ for a given type, and α is the coefficient of total photographic absorption due to inclination. Holmberg finds $\alpha = 0.28 \pm 0.07$ magnitude for Sc+ and Sc- galaxies (in the blue pg band) and $\alpha = 0.43 \pm 0.06$ for Sb+, Sb-, and Sa galaxies. Holmberg also finds that the function α (csc i - 1) fits the absorption only down to $i = 15^\circ$ (b/a ~ 0.33), below which the absorption reaches maximum values of 1.03 magnitude for Sc+ and Sc-, and 1.33 for Sb+, Sb-, and Sa. These upper limits to the correction are imposed to match the plot of S_0 versus b/a for $i < 15^\circ$.

Holmberg's choice of the form of the absorption function, $\Delta A = \alpha$ (csc i - 1), is a curious one. The choice of the cosecant function is easy to justify using the simple model of a plane-parallel absorbing layer of finite thickness, but the most general absorption function of this form would be $\Delta A = \alpha \csc i + \gamma$, where α is the coefficient of total absorption, and $\alpha + \gamma$ is the

absorption in a face-on galaxy. Holmberg chose $\gamma = -\alpha$, apparently so the term ΔA would not include information about face-on absorption, because $\alpha + \gamma = 0$, and the face-on correction depends on A_0 only. The choice of $\Delta A = \alpha$ (csc i - 1) is also curious because in determining the relation between reddening and inclination Holmberg assumed $\Delta E = \beta$ (1 - b/a), and showed it provided an accurate fit to the data. It seems reasonable that the same functional form, either (csc i - 1) or (1 - b/a), should apply to both ΔA and ΔE, particularly since the ratio of total to selective absorption is constant. Holmberg goes on to argue that if

$\Delta A = \alpha$ (csc i - 1)

then the face-on absorption, A_0, must be α. Thus,

$A = \Delta A + A_0 = \alpha$ (csc i - 1) + $\alpha = \alpha$ csc i.

Holmberg makes no corrections to diameters. He argues that a correction to the diameter due to inclination should be small because the decrease in diameter due to internal absorption should be offset by the increase due to greater path length through the galaxy. He also argues that the luminosity profile is so steep in the outer parts of galaxies that only small inclination corrections could be possible. There is no mention of diameter corrections due to Milky Way absorption. It should be noted that the lack of corrections to the diameter could cause systematic errors

in the surface magnitude, S_0, and thus in the total absorption, A.

Holmberg uses his data to show that the ratio of total to selective absorption, A/E, approaches 4.0 as the inclination goes to 90° (face-on), consistent with the values of R+1 measured within the Milky Way and with Holmberg's studies of the nearest galaxies. Holmberg also uses his data to derive corrections for disk light only (so-called "main bodies"), but this material will not be considered here.

Using his surface magnitudes corrected for inclination only, Holmberg assumes the Milky Way absorption is of the form csc |B| and calculates the photographic absorption, A_{pg}. His results are

$A_{pg} = (0.22 \pm 0.05)$ csc |B|

for the range $15^\circ < B < 88^\circ$, and

$A_{pg} = (0.26 \pm 0.07)$ csc |B|

for the more limited data with $|B| > 20^\circ$.

Before leaving Holmberg's system the author would like to point out that Holmberg was one of the first to construct a large, accurate catalog of galaxy observations and the first to calculate a complete sot of corrections. Holmberg provided the basis for all later studies, and even though the work has been criticized for ignoring corrections to angular diameters, it has withstood the test of time.

The HHV Corrections

The correction schemes presented in HHV I, II, III are applied to Holmberg's data and form the basis for the corrections in the RC2 system. The corrections are also applied to the data in the first reference catalog (de Vaucouleurs and de Vaucouleurs 1964, hereafter the BGC), but because that system has been replaced by the more useful RC2 it will not be discussed here. It should be noted that HHV had the Holmberg corrections as examples, so they were able to refine existing ideas. Their work is so broad that many of its important ideas must be omitted in this review.

In HHV I optical and radio parameters of spiral galaxies are defined. First, galaxies are divided into types in the familiar reference catalog system, in which a type S0 spiral is assigned T = 0, a type Sm is assigned T = 9, with the usual steps between. Next, diameters are defined. The isophotal major diameter is named D, with the Holmberg diameter labeled D_m, or occasionally, a. The isophotal major-to-minor axis ratio is R = a/b, with the Holmberg axis ratio labeled R_m. Here b is the isophotal minor diameter.

The angle of inclination, i, of a galaxy is given by

$$\cos^2 i = (q^2 - q_0^2)/(1 - q^2)$$

where $q = 1/R = b/a$, the observed axis ratio, and

$q_0 = c/a$, the true axis ratio for an oblate spheroid, where c is the diameter of the small axis of the spheroid. This gives $i = 0^o$ for a face-on galaxy, and $i = 90^o$ for an edge-on galaxy, just the reverse of Holmberg's system. HHV plot log R versus T to calculate the intrinsic flattening of each galaxy type, $q_0(T)$. This is a refinement on Holmberg's method, in which all galaxies are assumed to have $q_0 = 0.20$. HHV plot the two largest values of log R for each T using data from the BGC and the Holmberg catalog, then draw straight lines through the points to get $q_0(T)$.

HHV also gather 21-cm radio data to refine corrections when the optical data are few. They express the 21-cm flux, F_H, in terms of a hydrogen mass, M_H, for an assumed distance Δ,

$$F_H = 0.235 \int S(V)\,dV = M_H/\Delta^2$$

where S(V) is the monochromatic flux density for the whole galaxy, V is the radial velocity in km/s, and F_H is in 10^{-6} solar masses per Mpc^2. This flux may be left uncorrected, or may be corrected for self-absorption to set limits on the corrections.

In HHV II galaxy diameter corrections for inclination and Milky Way absorption are found, and surface brightnesses are corrected for internal absorption. The diameters are corrected first, presumably because they are

needed to determine the surface brightness used in the magnitude corrections.

Throughout the papers functional forms for corrections are chosen by considering simple models of spiral galaxies described in HHV III. Assume that a galaxy is an oblate spheroid, that the internal absorption is negligible in the outer regions of the galaxy, and that the volume emissivity in the outer parts is given by

$$E = E(r) = E_0 \, r^{-n}$$

Then the apparent diameter for an angle of inclination i is given by

$$D(i) = D(0) \, (a/b)^{1/(n-1)}$$

where D(0) is the diameter corrected for inclination, and a/b is the observed axis ratio. The equation may be rewritten

$$\log D(0) = \log D(i) - \frac{1}{n-1} \log R$$

in which D(i) and R are observed quantities. Thus, assume the correction for inclination is of the form -C log R, and solve for C. Solutions using optical data only give $\langle C \rangle \sim 0.5$ for all values of T. HHV believe this is too high due to selection effects, and calculate a new set of corrections using the radio fluxes.

Neglect 21-cm absorption, so the flux F_H is independent of inclination. Define a surface density $H = F_H/D^2$ where D is the apparent optical diameter. We

expect H to vary with galaxy type, T, and to decrease with increasing inclination (or axis ratio, R) because self-absorption undoubtedly occurs. In general H = H(T,R). Examine

$$K = \frac{\delta \log H}{\delta f(R)} = \frac{\delta \log F_H}{\delta f(R)} - 2 \frac{\delta \log D}{\delta f(R)}$$

but $\log D = A + C \log R$.

Now $\frac{\delta \log F_H}{\delta f(R)}$ was assumed to be zero, so

$$K = \frac{\delta \log H}{\delta f(R)} = -2C \frac{\delta \log R}{\delta f(R)}$$

If $f(R) = \log R$, then $K = -2C$. Using the observed values of H, F_H, D, T, and R, require

$\log H = \log F_H - 2 \log D = \alpha + \beta T - 2(\gamma + \delta T) \log R$

and solve for $\alpha, \beta, \gamma, \delta$. It is found that H increases with T ($\beta > 0$) as expected, and that D increases with R, but not significantly with T ($\gamma > 0$, $\delta \sim 0$). Using D_m and R_m, HHV find $\langle C \rangle \sim 0.24$ from the Holmberg data, but this is taken as an upper limit because self-absorption was neglected. If self-absorption is included, then F_H increases with i (thus, with R) so C is overestimated. Repeating the calculations with their model of self-absorption, they find $\langle C \rangle \simeq 0.16$ for the Holmberg data.

They adopt

$\log a(0) = \log a - 0.15 \log R_m$

where a is the Holmberg diameter. This correction is a surprise, for it uses C = 0.15, which is less than all the empirical values found by HHV. It is also a surprise because the radio data alone have been used to determine the optical inclination effect.

The diameters must also be corrected for Milky Way absorption. HHV begin with theoretical considerations. Let $\mu(x)$ be the luminosity distribution along the major axis, given in magnitudes-per-square-arcsecond in some well-defined photometric band, and let $(\delta \mu / \delta x |_a)$ be the gradient at x = a. The variation in semimajor axis per magnitude of absorption is

$\delta a = [\delta \mu / \delta x |_a]^{-1}$

If the galactic absorption function has value A magnitudes in the direction of the galaxy in question, then the corrected semimajor axis is

$a_0 = a + A\ \delta a = a \{1 + A(\delta a/a)\}$

or

$\log a - \log a_0 = -\log\{1 + A(\delta a/a)\}$

Assume $A = A_1\ f$, where f gives the dependence of the galactic absorption on galactic latitude, b, and perhaps other parameters. Also, assume

$A_1\ f(\delta a/a) << 1$

so

$$\log a - \log a_0 \simeq -0.43\ A_1\ f(\delta a/a)$$

and

$$\frac{\delta \log a}{\delta f} = -0.43\ A_1\ (\delta a/a)$$

HHV use typical values of A_1 and $(\delta a/a)$ to estimate

$$-0.016 \geq \frac{\delta \log a}{\delta f} \geq -0.032$$

for the Holmberg diameters.

A correction of the form B(T) csc|b| is assumed for the diameter (that is, f = csc|b|) but the optical data give uncertain results, so the radio data are used again. If the optical diameters, D, are too small at low latitudes then $H = F_H/D^2$ should be too large. Assume

$$\log H_{corr} = \log H - \epsilon\ f + \zeta$$

where f is the modified cosecant function of de Vaucouleurs and Malik (1969). Then for the Holmberg diameters

$$\log H - \log H_{corr} = 0.008\ f - 0.12$$

and

$$\frac{\delta \log D}{\delta f} = -0.004 \pm 0.017.$$

On the basis of the theoretical correction HHV adopt

$$\log D_m(f=0) = \log D_m + 0.02\ f$$

The approach to magnitude corrections for galaxy inclination used by HHV draws heavily on Holmberg's

method. Start with Holmberg's definition of the surface brightness

$S_0 = m_0 + 5 \log a$

where m_0 is the integrated magnitude corrected to the pole of the Milky Way. Here a is the raw major axis diameter, but the surface magnitude is likely to be improved by using the diameter corrected for inclination,

$\log a(0) = \log a - 0.15 \log R_m$

so define

$S_{0c} = m_0 + 5 \log a(0) = S_0 - 0.75 \log R_m$

where S_{0c} stands for the surface brightness calculated with the corrected diameter. Using Holmberg's data, a plot of $S_{0c}(pg)$ versus $b/a = R_m^{-1}$ shows that the maximum correction for inclination is reduced to 0.87 magnitudes for Sa and Sb galaxies and 0.56 magnitude for Sc galaxies (compare Holmberg's values of 1.33 and 1.03 respectively). Thus, using the corrected diameters decreases the dependence of surface brightness on inclination.

HHV argue that plots of S_{0c} versus $\log R_m$ suggest

$S_{0c} = S + p \log R_m$

where S and p depend on galaxy type, T, and luminosity class, L. Assume

$S_0^* = A + BT + CU + DL$

where A, B, C, D are constants, $U = \log R_m$, and

$S_0^* = m_{pg} - 0.2 f + 5 \log a(0)$

which includes the correction for Milky Way absorption of

0.2 f, a general result taken from de Vaucouleurs and Malik (1969), where f is a modified cosecant function. Solutions give the inclination correction

$CU = C \log R_m = (1.22 \pm 0.16) \log R_m$

if L is known, or

$CU = (1.35 \pm 0.17) \log R_m$

if L is not known, giving maximum corrections of 1.12 magnitude and 1.24 magnitude respectively for the flattest galaxies, type Sd, $q_0 = 0.12$.

Using the calculated values of the constants, HHV analyze surface brightness in general. They find the error in computed surface brightness, S_0^*, is 0.313 magnitude, most of which is due to the uncertainty in D_m, the Holmberg diameters. They conclude that the cosmic dispersion in S_0^* is 0.2 magnitude or less for fixed values of T, R_m, and L.

The inclination correction to surface brightness is calculated using the 21-cm data. The analysis is similar, and no significant difference is found in the correction.

Further investigation by HHV reveals that the curve relating S_0 to b/a may be linearized by changing the variable describing inclination to U = log(sec i). Examine the relation between S_0 and T, log(sec i), and L, with the constraint that $i < 80^\circ$, for beyond that inclination the absorption depends on the detailed distribution of absorbing material in the galaxy. It is

found

$S_0^* = 14.75 + 0.040\ T + 0.72 \log(\sec i) + 0.083\ L$

and the correction for inclination is

$A_0(i) = S_0^*(i) - S_0^*(0) = (0.72 \pm 0.16) \log(\sec i)$

independent of type, T. This correction gives the "face-on" magnitude, not the "dust-free" magnitude.

The Sandage and Tammann Corrections

In their years of work on the distance scale Sandage and Tammann have also adopted a set of corrections for the Holmberg magnitudes, but none for the diameters. Using new photometry in several bands Sandage (1973) rederives the Milky Way absorption in blue light as

$A_B = 0.132(\csc|b| - 1)$ for $|b| \leq 40^\circ$, with A assumed to be zero for $|b| > 50^\circ$, and a smooth transition between the two. Sandage assumes the functional form $(\csc|b| - 1)$, it is not determined from the data.

Sandage and Tammann (1974b) adopt a "face-on" inclination correction, for Sc galaxies only, similar to Holmberg's

$A(i) = 0.28\ (\csc i - 1)$

in the blue photographic band, with the assumption that $\csc i = a/b$, where a/b is calculated from the BGC. Thus, the catalogs are mixed. No correction is specified for galaxies of other types. To correct for Milky Way absorption they adopt the unusual correction

$A_B = 0.219\ (1.192 - \tan b)\ \csc b$

$= (0.26 - 0.219 \tan b)\ \csc b$

for $|b| \leq 50^o$, and $A_B = 0$ otherwise.

Sandage and Tammann (1976b) adopt $A(i) = \alpha\ (a/b)$, which gives a "dust-free" and "face-on" correction in order "to make the luminosities of early-type and late-type spirals more comparable." No source of a/b values is specified, so it is assumed to be the Holmberg catalog. Holmberg's values for α are assumed, $\alpha = 0.28$ magnitude Sa, Sb; $\alpha = 0.43$ Sbc to Sdm; $\alpha = 0.15$ Sm, Im. The correction to the galactic pole is assumed to be $0.12\ (\csc|b| - 1)$ for $|b| \leq 50^o$, with zero correction above 50^o and a smooth transition between. Because the correction is zero at the pole, correcting to the pole is the same as correcting to outside the Milky Way. This is not the case with the Holmberg and HHV formulations. The corrections from Sandage and Tammann (1976b) will be adopted as representative of the Sandage and Tammann corrections.

The RC2 Corrections

Corrections in the RC2 system are derived in nearly the same way as the HHV corrections to Holmberg's data. First, correct the diameter for inclination by

$\log D(0)_{25} = \log D_{25} - 0.235 \log R_{25}$

where D_{25} is the diameter in tenths of arc minutes at the

twenty-five-magnitude-per-square-arc-second isophote in the B band of the UBV system, R_{25} is the corresponding axis ratio, and 0.235 is determined by repeating the F_H/D^2 test of HHV, supplemented with a new test (whose details are not given in the RC2) in which it is required there be no correlation between log R_{25} and log $D(0)_{25}$ for first-ranked cluster galaxies. The diameter is corrected for Milky Way absorption by

$$\log D_0 = \log D(0) + A_B \, G_{25}^{-1}$$

where A_B is the Milky Way absorption in magnitudes in the direction of the galaxy in question, and

$$G_{25}^{-1} = \frac{\delta \log D_{25}}{\delta \mu}$$

which is calculated to be

$$G_{25}^{-1} = 0.12 - 0.007 \; T.$$

The raw magnitudes, given as B_T, the total asymptotic magnitude in the B band, are corrected to face-on by

$$A(i) = 0.70 \log(\sec i)$$

essentially the same as in HHV II, but slightly lower due to the different passband. This is rewritten as

$$A(i) = \alpha(T) \log R_{25}$$

for galaxies with unknown i. Here $\alpha(T) = 0.8$ for most spirals.

The magnitudes are corrected for Milky Way absorption by A_B. This includes a modified cosecant function which takes into account the variation of absorption in both

galactic latitude and longitude. The magnitudes are corrected for redshift by

$K'_B(T)cz$

where

$K_B(T) = [0.075 - 0.010\ (T-3)] \times 10^{-4}$

for most spirals.

The final corrected magnitude may be written

$B_T^0 = B_T - A_B - A(i) - K'_B(T)cz.$

B_T^0 is a face-on magnitude, but not a dust-free magnitude.

The RSA Corrections in the RC2 System

Sandage and Tammann have also developed corrections to the B_T magnitudes of the RC2 system, but again do not offer corrections to diameters. The corrections are explained in the introduction to the RSA. They adopt an inclination correction to the magnitude,

$A^i = \alpha + \beta \log(a/b) \leq A^i_{max}$

For log(a/b) they use log R_{25} from the RC2, where for Sa-Sb galaxies $\alpha = 0.43$, $\beta = 1.34$, $A^i_{max} = 1.33$; for Sbc-Sd $\alpha = 0.28$, $\beta = 0.88$, $A^i_{max} = 0.87$; for Sdm-Im $\alpha = 0.14$, $\beta = 0.44$, $A^i_{max} = 0.43$. This gives a face-on correction of log(a/b) and a dust-free correction of α, so the result is a dust-free magnitude.

The correction to the magnitude for Milky Way absorption is taken from Sandage (1973),

$A_i = 0.132\ (\csc|b| - 1)$ for $|b| < 50^o$

$A_i = 0$ for $|b| \geq 50^o$

This correction assumes the existence of absorption-free polar windows. The same corrections are assumed by Kraan-Korteweg (1982), so the $B_T^{(0,i)}$ magnitudes in that catalog are in the RSA system.

The Unique Corrections of Rubin et al.

Rubin, Thonnard, Ford, Roberts, and Graham (1976) use their catalog of Sc galaxies to derive a set of corrections which apply to Sc galaxies only. Their magnitudes for 96 galaxies from Graham (1976) are derived from corrected photoelectric aperture photometry in the B and V bands. The B magnitudes are reduced to a standard aperture equal to the galaxy diameter, so they are independent of galaxy size. They may be corrected to total magnitudes by the constant -0.35 ± 0.15, although the correction is not applied in the paper. This list of magnitudes is expanded to a total of 201 by the addition of the magnitudes of all galaxies from the Zwicky catalogs (1961-1968) which have Zwicky magnitudes between 14.0 and 15.0 and are found by Rubin et al. to be of types ScI or ScII. The overlap of the two magnitude sublists allows recalibration of the Zwicky magnitudes. They find

$$m_{Graham} - m_{Zwicky} = -(2.43 \pm 0.41) \log d + (0.05 \pm 0.09)$$

Here d is the diameter in minutes of arc measured by Rubin

et al. from the PSS prints using an eyepiece calibrated in tenths of millimeters. The data have been compared with the blue diameters of the UGC (Nilson 1973), which are known to be accurate, and the agreement is good,

$< d \text{ (Nilson)} / d \text{ (Rubin)} > = 1.18 \pm 0.02$

for one galaxy $\sigma = 0.19$, and axis ratio

$< b/a \text{ (Nilson)} / b/a \text{ (Rubin)} > = 0.96 \pm 0.01$

for one galaxy $\sigma = 0.14$. The catalog also includes new determinations of the radial velocities.

The data are used to define the Hubble modulus, HM,

$$HM = \log H - 0.2 \log M - 5 = \log V_c - 0.2\, m$$

where H is Hubble's constant in km/(s*Mpc), M is absolute magnitude, V_c is radial velocity with respect to the center of the Local Group, and m is apparent magnitude. Notice that HM can be calculated from H and M, or from V_c and m. The latter is usually easier. HM is the parameter of choice for investigating the uniformity of the Hubble flow, but to use it in this way all known systematic effects must be removed from the data. To do this, first a minimum-bias subset of the Sc catalog is chosen. To avoid the Malmquist bias inherent in a magnitude-limited sample, a velocity-limited subset is chosen as the best available approximation to a distance-limited sample. For $3500 \text{ km/s} < V_c < 6500 \text{ km/s}$ it is shown that the Malmquist bias is minimized, so the 96 galaxies in this velocity range are kept for further calculation.

Here, a word on the method of calculating the corrections is necessary. Rubin et al. require that all known systematic effects be removed from V and m, so

$HM = \log V_c - 0.2\ m_c$

$m_c = m_{observed} - \Delta m_b - \Delta m_i - \Delta m_{LC} + \Delta m_d$

where Δm_b corrects for Milky Way absorption, Δm_i for inclination, Δm_{LC} for difference from van den Bergh luminosity class I, and Δm_d for diameter. No K-correction is applied. From the literature, Rubin et al. find best guesses for each correction. Then, in an iterative procedure, the Hubble modulus is calculated using those values as a starting point, but with the correction to be determined left out, so the variation in HM gives the correction. The newly-calculated correction is then inserted, HM is calculated with a different correction left out, the correction is determined, and so on through two complete iterations. This procedure is found to converge very quickly.

The Milky Way correction, Δm_b, is assumed to be of the form $A_B\ (\csc|b| - 1)$, so the correction may be thought of as to-the-pole only, or as zero absorption at the pole only. The calculations give $A_B = 0.15 \pm 0.03$ magnitude. The inclination correction is assumed to be

$\Delta m_i = A_i\ (\sec i - 1)$

where i is calculated using an early formula from Holmberg (1946)

$\cos^2 i = 1.042\ (b/a)^2 - 0.042.$

This correction is essentially the same as the one from Holmberg (1958), except for the different formula for the inclination. The iteration gives $A_i = 0.12 \pm 0.08$ magnitude, much less than Holmberg's value of 0.28 for Sc galaxies.

The correction for change of luminosity class is assumed to be of the form

$\Delta m_{LC} = A_{LC}\ (LC - 1)$

where LC is the luminosity class. The result, $A_{LC} = 0.18 \pm 0.09$ magnitude, is much less than the original determination of 0.60 by van den Bergh (1960).

The diameter correction is non-conventional and more complex, but the authors find it greatly reduces the scatter in their Hubble diagram, acting as a luminosity classification by diameter--a known luminosity indicator. The correction has three parts: an increase in diameter with inclination, a decrease in diameter with decreasing galactic latitude, and a decrease in diameter with increasing path length through the Earth's atmosphere at the time of observation.

The inclination effect on the diameter is shown to be independent of the inclination effect on magnitude, because the magnitude correction has already been made. The diameter correction takes the form

$\log(\kappa V_c d) = p \log(\cos i) + \text{const.}$

where κ is a constant so $\kappa V_c d$ is the linear diameter of the galaxy in megaparsecs. The value of p must be determined, and for the Sc sample $p = 0.11 \pm 0.12$, consistent with $p = 0$, so no correction is applied. Thus, after the magnitude is corrected for inclination, there is no need to correct the diameter for inclination.

The observed diameters of galaxies are known to decrease toward the galactic plane. Rubin et al. use a surface brightness analysis similar to Holmberg's (1958), the assumed form is

$$\Delta d_b = D_d \ (\csc|b| - 1)$$

and the iteration gives $D_d = 0.096 \pm 0.021$. This corrects the diameter to the pole of the Milky Way.

A similar decrease in observed diameter occurs when the galaxy's light passes through the Earth's atmosphere, the size of the effect depending upon the zenith distance of the galaxy at the time of observation. The correction is written as

$$\Delta d_z = D_z \ (\sec z - 1)$$

where z is the zenith angle, and $D_z = 0.081 \pm 0.028$ from the iteration. This corrects the diameter to the zenith.

The corrected diameter is

$$d_{b,z} = d_{obs} \ [1 + D_z \ (\sec z - 1)] \ [1 + D_b \ (\csc|b| - 1)]$$

An analysis of the variation of the Hubble modulus with linear diameter, $\kappa V_c d$, gives the diameter correction to the magnitude,

$m_d = A_d\ [\log(\kappa V_c\ d_{b,z}) - 3.94]$

where $A_d = 2.75 \pm 0.25$ magnitude from the iteration.

Criticisms of these corrections are directed mainly at the sample (Fesenko 1979, 1980). The method is new and exciting, for it seems more complete than the other systems, and the iterative method should allow determination of all the effects at once. Unfortunately, the ScI list is small, only 96 galaxies in the unbiased sample, and the published results apply only to ScI galaxies, except for the value of A_B. A larger sample, including other Hubble types, would be difficult to build, but could yield a well-accepted, consistent set of corrections.

Other Correction Schemes

Several other correction schemes have been published. Even though these schemes do not have a large following, they do indicate where researchers believe the well-accepted corrections are inadequate.

Krumm and Salpeter (1979) and Helou et al. (1981) work with galaxy magnitudes in the RC2 system, but cite evidence in the literature that the Milky Way absorption and galaxy inclination corrections in the RC2 may be too large. They adopt half of the RC2 corrections, using

$B^* = (B_T^0 + B_T)/2$

where B_T^0 is the corrected blue magnitude from the RC2 and B_T is the uncorrected magnitude.

Dickel and Rood (1978) work in the Holmberg system, but adopt the HHV form of the correction to diameters for inclination, taking $D_H \propto D_0\ r^n$, where D_H is the Holmberg diameter, r is the Holmberg axis ratio, and n is taken to be 0.3.

They adopt a Milky Way absorption of 0.22 csc|b| from Holmberg (1958, 1974), and repeat the analysis of Holmberg (1958) for the inclination correction to magnitudes, taking the correction to be of the form α sec i. From their data they determine α = 0.17 magnitude for Sa-Sbc galaxies and α = 0.23 for Sc-Sdm galaxies. Holmberg (1958) found α = 0.43 for Sa, Sb-, and Sb+; α = 0.28 for Sc. Rubin et al. found α = 0.12 for Sc galaxies only. The differences among these systems are not yet understood.

Tully (1972), working in Holmberg's magnitude system, objects to the inclination corrections for Holmberg diameters proposed in HHV II. The diameter correction is calculated from radio observations, which is a surprise to begin with, and Tully objects to the lack of homogeneity in the radio data and the analysis. Tully finds that if the diameter correction for inclination is applied, then the magnitude correction for inclination must be reduced, but he argues that the unreduced magnitude correction

alone should be applied, eliminating the diameter correction entirely. Rubin et al. reach the same conclusion.

Fisher and Tully (1981) propose their own corrections in the Holmberg system. The diameter of a galaxy is corrected only for Milky Way absorption, by

$$a_H^b = a_H \, f_a$$

where a_H is the raw Holmberg diameter and a_H^b is the corrected diameter. Also,

$$f_a = \mathrm{dex}(0.215 \, A_b^2)$$

where dex is the base-ten exponential function, and

$$A_b^2 = -0.149 + (6.41 \times 10^{-4}) \, N_H$$

as in Burstein and Heiles (1978), but the term describing the variation in gas-to-dust ratio has been dropped. The term N_H is the column density of HI from Burstein and Heiles.

The magnitude of a galaxy is corrected by the same A_b for Milky Way absorption, and Fisher and Tully propose the novel inclination correction

$$A_i = -\alpha \, [\ln\{\exp(-\sec i) + \beta\} + 1]$$

with $\alpha = 0.3$ magnitude, $\beta = 0.01$. This function reduces to

$A_i \sim \alpha$ (sec i -1) for i small

$A_i \sim \alpha$ (const.) for i large

Numerically it is similar to the correction of Sandage and

Tammann (1974a), who use $A_i = 0.28\ (a/b - 1)$ for Sc galaxies only.

CHAPTER 6

ADOPTED CORRECTIONS

Corrections to Holmberg Magnitudes

The corrections to the Holmberg magnitudes calculated by Holmberg (1958), HHV, and Sandage and Tammann (1976b) are adopted for the calculations in this thesis. Let A_B be the correction for Milky Way absorption in the blue (hence the B) and A(i) be the correction for inclination. Let a be the galaxy's major diameter, let b be the minor diameter, and let q(T) be the intrinsic smallest-to-largest axis ratio for a spiral galaxy of type T, assumed to be an oblate spheroid. There is possible confusion here, for b also stands for galactic latitude, but the latitude always appears by itself as the argument of a trigonometric function, while the minor diameter always appears in association with the major diameter, a. Note that Holmberg uses the old galactic latitude, B, and HHV adopt the modified cosecant function, f, from de Vaucouleurs and Malik (1969).

The corrections formulated by Holmberg are

$$A(B) = 0.22 \csc|B|$$

$A(i) = \alpha \csc i$

$\sin^2 i = \{(b/a)^2 - (0.20)^2\}/\{1 - (0.20)^2\}$.

In the system of HHV

$A(B) = 0.2\ f$

$A(i) = 0.72 \log(\sec i)$

$\cos^2 i = \{(b/a)^2 - q(T)^2\}/\{1 - q(T)^2\}$.

In the system of Sandage and Tammann

$A(B) = 0.12\ (\csc|b| - 1)$ $\quad |b| < 50^\circ$

$A(B) = 0$ $\quad |b| > 50^\circ$

$A(i) = \alpha\ (a/b)$.

Corrections to Holmberg Diameters

Diameter corrections in the Holmberg system come from HHV only. Here, again, f is the modified cosecant function of de Vaucouleurs and Malik (1969). The corrected diameter, a(0), is

$\log a(0) = \log a - 0.15 \log(b/a) + 0.02\ f$

It must be noted that HHV III take $0.02\ f \sim 0$ for Virgo galaxies.

Corrections to the B Magnitudes of the RC2

Corrections to the RC2 magnitudes come from the RC2 and the RSA, but there is so much controversy over the formulation of Milky Way corrections in the RC2 that alternate corrections are available from several sources. Of those, two, $A(B) = 0$ at the poles ($|b| > 50^\circ$ in the RSA

system) and the individual reddenings from Burstein and Heiles (1984), are adopted here. The reddenings are transformed to absorption values with the assumption R+1 = 4.0. Here R_{25} is the RC2 axis ratio, S_N and S_S are functions in λ and b from de Vaucouleurs and Buta (1983), and C is a modified cosecant function. The RC2 corrections are

$A(B) = 0.21\ (1 + S_N \cos b)\ |C|$ in the northern hemisphere

$A(B) = 0.19\ (1 + S_S \cos b)\ |C|$ in the southern hemisphere

$A(i) = 0.70 \log(\sec i) = 0.80 \log R_{25}$.

The alternate Milky Way absorption corrections are

$A(B) = 0$ similar to the RSA

$A(B) = 4.0\ E(B-V)$ from Burstein and Heiles.

The RSA corrections are

$A(B) = 0.132\ (\csc|b| - 1)$ $\quad |b| < 50^\circ$

$A(B) = 0$ $\quad |b| > 50^\circ$

$A(i) = \alpha + \beta \log(a/b) < A^i_{max}$.

Corrections to RC2 Diameters

These corrections come only from the RC2. Let D be the corrected diameter, D_{25} be the raw RC2 diameter, R_{25} be the RC2 axis ratio, and A_B be the Milky Way absorption from the RC2. Then

$\log D = \log D_{25} - 0.235 \log R_{25} + A_B\ (0.12 + 0.007\ T)$.

CHAPTER 7

THE CHOICE OF VIRGO GALAXIES FOR COMPARISON

Despite the importance of the Virgo cluster, a head-to-head comparison of the published Virgo membership lists has not been attempted before. Such a comparison is made here to determine lists of the largest, brightest, smallest, and faintest Virgo members. The membership lists differ, particularly over the small and faint galaxies. Some of the differences must be due to uncertainties in the magnitudes and radial velocities, that is, uncertainties in the fundamental data, which are always worst for the faint objects.

Important lists of Virgo galaxies are given by HHV III, de Vaucouleurs and de Vaucouleurs (1973), Sandage and Tammann (1976a), Turner and Gott (1976), Sulentic (1980), Sandage and Tammann (1981, the RSA), and Geller and Huchra (1983). Reaves (1983) has also published a large list of dwarf galaxies in Virgo. These lists have been used to choose spiral galaxies to compare with M31 and M33. The lists agree that NGC 4569 is probably the brightest and largest spiral in circle of 6° radius centered on the Virgo region, but there is some doubt about its membership in the Virgo cluster due to its large negative radial

velocity. Mould, Aaronson, and Huchra (1980) give NGC 4569 zero weight in their calculations, yet state, "...while it might be argued that NGC 4569 is a foreground object (it is, in fact, the largest spiral in the 6^{o} circle), its negative systematic velocity makes its most probable location the cluster core itself." It is found by de Vaucouleurs and de Vaucouleurs (1973) that NGC 4569 may be a foreground object, but Helou, Salpeter, and Krumm (1979), using the method of Tully and Fisher (1977), find that it cannot be stated with certainty that it is a foreground galaxy, and Burbidge and Hodge (1971) find that it is a member of the cluster. Sandage and Tammann (1976a) write, "The only individual galaxies that are certain members of the cluster are those with negative redshifts." NGC 4569 is one of those. As will be shown in Chapter 8, the spiral galaxies in Virgo are known to have lower hydrogen-mass-to-blue-light ratios than field galaxies, and NGC 4569 does have a low value of that ratio. Because NGC 4569 is listed as a member by all the lists it is taken to be a member for the purposes of this paper, however, other galaxies will be included in a list of the largest and brightest so the results of the calculation do not depend upon one galaxy of debatable membership.

To determine which are the largest and brightest Virgo galaxies the corrected diameters and magnitudes of

the largest and brightest members form the lists of HHV III, Turner and Gott (1976), and Geller and Huchra (1983) were tabulated using data from the RC2, the RSA, and Holmberg (1958). The galaxies most consistently at the tops of the lists were taken to be the largest and brightest. The largest are NGC 4569, 4517, 4192, and, 4321, roughly in order of decreasing size. The brightest include NGC 4569, 4321, and 4303, roughly in order of increasing magnitude.

Choosing a list of the faintest and smallest members of the Virgo cluster is more difficult, for none of the catalogs of galaxy data claim to be complete to the required magnitude, fainter than B = 14.0. After reviewing the membership lists and the RC2, RSA, and Holmberg catalog a reasonable list has been compiled. This list relies most heavily on the membership list of Geller and Huchra (1983) (which has the faintest limiting magnitude), on the associated list of galaxy data in the Center for Astrophysics radial velocity catalog of Huchra et al. (1983), and on Reaves's list of dwarf galaxies. For all but the dwarfs the radial velocity must be known and consistent with membership in the cluster for the galaxy to be included here. The radial velocities of most of the dwarf galaxies are not known, but Reaves argues that they are members on the basis of their distribution. At the magnitudes involved in choosing faint, small

galaxies the RSA provided the least data, but that catalog is not claimed to be useful for such faint galaxies. The list of Kraan-Korteweg (1982), which gives magnitudes in the RSA system, was important.

The small, faint galaxies were chosen by again tabulating data from the RSA, RC2, and Holmberg (1958) catalogs, but there is not general agreement among the membership lists for faint galaxies, and few studies center on small ones. To compile a reasonable list the galaxies were put in two categories, normal galaxies (that is, non-dwarfs) and dwarfs, and the faintest in either category were also assumed to be the smallest. Thirty-nine of the dwarf galaxies in the list of Reaves (1983) also appear in the data lists of de Vaucouleurs and Pence (1979). These dwarf spirals, irregulars, and ellipticals were taken to be members of the Virgo cluster on the basis of their distribution only. Because M33 is brighter and larger than all the dwarf galaxies in the Local Group it is assumed to be brighter and larger than all the dwarfs in Virgo. It should be noted, however, that the list includes the brightest, largest dwarfs in Virgo, which could rival M33 in size and brightness. The corrected data for these galaxies come only from the catalog of de Vaucouleurs and Pence (1979) because the galaxies are too small and faint to be included in the other catalogs. This catalog is in the RC2 system.

The faint, small normal galaxies were chosen from the Virgo membership lists of Geller and Huchra (1983), Kraan-Korteweg (1982), the RSA, Turner and Gott (1976), Tammann (1972), and HHV III, with the additional requirements that each galaxy must have a known radial velocity, be a member of either the S or S' cloud, and be of late Hubble type, preferably type Sc or later. It has long been suspected that the later Hubble types have fainter average absolute magnitudes, and this has been established by Strom (1980) and in HHV I. The faintest, smallest galaxy common to all six lists is NGC 4299. It is included in the list because of the agreement that it is a member, but there is no guarantee it is smaller and fainter than M33. Sixteen small, faint galaxies are common to three or more of the lists, and of these NGC 4234, 4630, and 4633 are included here for comparison because they are among the faintest and representative of the smallest. Twenty more galaxies are found in two or more catalogs, and of these IC 3258 and IC 3521 are included here for comparison as being representative of the group. On average, these galaxies are smaller and fainter than the previous ones, but properties do overlap between the groups. Many more galaxies appear in only one membership list, but they are not used here because their membership is less certain. It should be noted that the membership lists are not

independent; often material from one list was used in compiling another.

Of the many dwarf galaxies from the list of Reaves (1983) only IC 3665 and IC 3073 are kept. They are the smallest, faintest dwarf galaxies with data in the catalog of de Vaucouleurs and Pence (1979), and are significantly smaller and fainter than the galaxies in the previous groups. It should be noted that the largest, brightest dwarf, UGC 7557, is close to NGC 4633 in magnitude, but is very much larger, even larger than NGC 4299.

This list of small, faint galaxies is not without controversy. NGC 4234 has a large positive radial velocity, and 4299 is not included in Virgo distance calculations by de Vaucouleurs and Bollinger (1979), presumably because of its small radial velocity, +107 km/s. It is also the companion of 4294 (Peterson 1979). Nevertheless, the list will be kept because these galaxies are representative members of much larger groups with similar properties. Some of these galaxies must be cluster members.

CHAPTER 8

ADOPTED DATA

Disputes in the Raw Data

Surprisingly, there are only two significant disputes in the raw data, over the diameters of M31 and M33 in the Holmberg system. In the case of M31 the observed diameter is given by Holmberg (1958) as 197 arcminutes at the 26.5 magnitude-per-square-arcsecond isophote in the blue photographic band. Interpolation for the present calculation of the reobserved profile from de Vaucouleurs (1958) gives 245 arcminutes at the 26.5 magnitude-per-square-arcsecond isophote in the B band, the equivalent of Holmberg's isophote. Extrapolation for the present paper of the more recent photometric profile from Hodge and Kennicutt (1982) suggests 240 arcminutes in B. They did not use their data to calculate the size of such faint isophotes, and probably did not intend their data for such use, but the agreement with the measurement of de Vaucouleurs is remarkable. This suggests that Holmberg's value is too small, although still useful within reasonable error bars. For the calculations in the

Holmberg system, both raw diameters, 197 and 240 arcminutes, are adopted.

A similar disagreement exists over the diameter of M33. Holmberg (1958) gives 83 arcminutes at 26.6 magnitude in the blue photographic band, interpolation of the profile from de Vaucouleurs (1959) gives 75 arcminutes at 26.5 in B. Again, both values are adopted.

Disputes in the Corrections

The dispute over the Milky Way absorption at the poles has already been reviewed in Chapter 4, and only two more significant disputes remain. The first arises in the Milky Way correction to the magnitude of M31. The tabulated value of A_B, called A^0 in the RSA, is 0.64 magnitude, while the value of A_B for M32 is 0.22. The value 0.22 is calculated for both galaxies using the correction formula in the RSA, but the value 0.64 for M31 cannot be reproduced. It is assumed that M31 and M32 should suffer similar Milky Way absorption due to their proximity. A brief survey of the literature may settle this disagreement. In the RC2 the correction is 0.41 magnitude for M31 and 0.40 magnitude for M32. Burstein and Heiles (1984) list 0.32 magnitude for M31 and 0.31 for M32. Assuming R+1 = 4.0, the reddening of M31 found by McClure and Racine (1969) gives 0.44 magnitude. Thus, the Milky Way absorption for M31 in the RSA is probably too

high by 0.2 to 0.4 magnitude. For the calculations in the RSA system two values of B_T^0 are adopted, 2.71 as listed in the RSA, and 3.13 as found from the RSA correction formula.

The second dispute is over the type of inclination correction to apply to galaxy magnitudes. Holmberg (1958) was interested primarily in the light from the stars in disks of spirals, so his corrections were formulated to remove the effects of inclination and dust. This form of correction is adopted by Sandage and Tammann (1974b, 1976b) and used in the RSA. Such a correction is called face-on and dust-free, and is sometimes said to allow for "total internal absorption," as in the RSA.

The other correction, to face-on only, is favored by de Vaucouleurs and his many coworkers in the RC2 and in HHV. This preference seems to arise from the interest of de Vaucouleurs in overall, or integrated properties of galaxies. Thus, the corrections in the RC2 and HHV are face-on, but not dust-free. To quote from the introduction to the RC2, page 33, "The face-on magnitude is the proper measure of intrinsic luminosity for most applications, for example for use as distance indicators, in mass/light or optical/radio emission ratios, etc."

In the three face-on and dust-free formulations the correction for dust is 0.28 magnitude for Sc galaxies and 0.43 magnitude for Sa-Sb galaxies. Applying such a

correction would change the calculated magnitudes, but it would not change the limits to the distance scale because M31 and all the largest, brightest Virgo spirals require the Sa-Sb correction. Similarly, M33 and all the small, faint Virgo galaxies require the Sc correction.

In the RC2, page 33, a dust-free correction of 0.17 magnitude is suggested for all spirals, but it is pointed out that this correction must be uncertain due to the unknown distribution of the dust. Applying a correction of 0.17 magnitude to all the galaxies would have no effect on the calculated limits to the distance scale, so it will not be applied.

The dispute is real, but for the present calculations choosing one correction over the other would have no effect, so the cataloged corrections will be left unchanged. The magnitudes corrected with the systems of Holmberg (1958), Sandage and Tammann (1976b), and the RSA will be face-on and dust-free, while the magnitudes in the systems of the RC2 and HHV will be face-on only. Under other circumstances the difference between the corrections could be important, so future research should be dedicated to resolving the dispute.

Errors and their Propagation

The errors in the corrected magnitudes are difficult to estimate. On page 9 of the RSA likely errors are given as 0.2 magnitude in the raw B magnitude, 0.15 magnitude for Milky Way absorption, and 0.25 magnitude for the inclination and dust correction. This gives a mean error of 0.35 magnitude, but it is expected that the error should be smaller for well-observed galaxies such as M31, M33, and the brightest Virgo spirals.

Improved estimates of the errors can be made by examining the catalogs. Holmberg (1958) lists mean errors in magnitudes according to the number of observations of each galaxy. These are adopted and propagated through the corrections of the Holmberg magnitudes, but it should be noted that these errors seem small, 0.060 to 0.027 magnitude, and are probably relative errors (not absolute errors) in which case they would be underestimates. Errors in the Holmberg diameters are calculated in HHV II by comparing them with diameters in the BGC. The one-sigma error in the log of the Holmberg diameter is found to be 0.045, and this value is adopted and propagated through the present calculations.

The RC2 includes the errors in B_T, log D_{25}, and log R_{25}. These, too, are adopted and propagated through the calculations. The RC2 data are mostly transformed

from other catalogs, so the errors represent the spread over all the catalogs. Again, the errors are probably internal and not absolute, so they may be too low. Typical errors are 0.03 to 0.07 magnitudes in B_T for the bright galaxies and up to 0.15 magnitudes for the faint ones. Errors in log D_{25} and log R_{25} are typically 0.02 for large galaxies and up to 0.05 for small ones. When errors are not available, as for RSA data, the RC2 errors are assumed.

The errors of the corrections are somewhat harder to determine. Starting with the inclination correction to magnitude, A(i), HHV find the correction is $A(i) = (0.72 \pm 0.16) \log(\sec i)$, including a twenty-two percent error. For the present calculations an error of twenty-five percent is assumed, consistent with the determination of HHV, but probably an underestimate. The error in the magnitude correction for Milky Way absorption, A_B, is calculated by Holmberg (1958), where the correction is $(0.22 \pm 0.05) \csc|B|$. Here the error of 0.05 magnitude is adopted for all the A_B corrections. This error is about the same as the uncertainties in the galaxy counts and E(B-V) values given in many of the studies outlined in Chapter 4.

The error in the inclination correction to diameters is calculated in the RC2, where the correction is $(0.235 \pm 0.050) \log R_{25}$, so the error is twenty-one

percent of the correction. For the calculations in this paper an error of twenty-five percent will be assumed for correction schemes. This is consistent with the error in the RC2, but is probably an underestimate.

The error in the correction to diameters for Milky Way absorption is not clearly stated in any of the catalogs, so improvisation must take over. The correction has the form of a constant times the Milky Way absorption, A_B, where the constant is small; 0.02 in the HHV corrections and (0.12 - 0.007 T) in the RC2. If the error in A_B is 0.05 magnitude, then the error in the correction to the log of the diameter is of order 0.005, or 1.2 percent of the diameter. An error of 0.005 in the log is propagated through the calculations.

This set of errors in the corrections is subject to criticism because it has been assembled from many different sources in a patchwork fashion. It is expected that future calculations with better data will supersede these errors, but, to the author's knowledge, this is the first time such a set of errors has been assembled and propagated through the calculations. It is requested that the reader view these estimates of the errors as a first attempt at a poorly-defined problem.

Tables of Corrected Data

The data and results are so extensive that they cannot all be included in this chapter. Instead, the complete tables of data are in Appendix B, and only the data in the RC2 system are included here. Of all systems, the RC2 is the most frequently used, and, as will be seen in Chapter 10, the results in this system are similar to the results in the other systems. The RC2 system is also the only one with data for all the galaxies.

Tables 2 through 7 show the RC2 system data for Local Group and Virgo cluster galaxies. The tables show that NGC 4569 is the brightest and largest member of the Virgo cluster, but NGC 4321 is only slightly smaller and fainter. The difference in resulting distance modulus and Hubble's constant must be small. The tables also show that NGC 4234 and NGC 4633 are remarkably small and faint for galaxies not classified as dwarfs, making them good spirals to compare with M33.

The complete tables in Appendix B show that the RSA magnitudes of all galaxies are smaller (brighter) than magnitudes in the RC2. This is because of the larger correction for inclination in the RSA. The tables also show that the errors in the RSA system are larger than those in the RC2. This is because the error increases as the inclination correction increases.

Table 2. Corrected RC2 system diameters of Local Group galaxies

Galaxy	log D
M31	3.19 ± 0.03
M33	2.77 ± 0.03

Table 3. Corrected RC2 system magnitudes of Local Group galaxies.

Galaxy	Magnitude
M31	3.59 ± 0.11
M33	5.79 ± 0.07

Table 4. Logarithms of corrected RC2 system diameters of the largest Virgo cluster galaxies.

Galaxy	log D
NGC 4569	1.93 ± 0.03
NGC 4517	1.85 ± 0.05
NGC 4192	1.89 ± 0.04

In general, the differences in the several correction schemes does not cause much difference in the final results. The only notable exception is the magnitude of M31 in the Holmberg system with the corrections of Sandage and Tammann (1976b), which is suspiciously large.

Table 5. Corrected magnitudes in the B system of the RC2 for the brightest Virgo cluster galaxies.

Galaxy	Magnitude
NGC 4569	9.78 ± 0.11
NGC 4321	9.86 ± 0.08
NGC 4303	9.97 ± 0.08

Table 6. Logarithms of corrected RC2 system diameters of the smallest Virgo cluster galaxies.

Galaxy	log D
NGC 4299	1.25 ± 0.04
NGC 4234	1.12 ± 0.04
NGC 4630	1.21 ± 0.04
NGC 4633	1.25 ± 0.04
IC 3258	1.21 ± 0.05
IC 3521	1.06 ± 0.05
IC 3665	1.01 ± 0.05
IC 3073	1.03 ± 0.05

Table 7. Corrected magnitudes in the B system of the RC2 for the faintest Virgo cluster galaxies.

Galaxy	Magnitude
NGC 4299	12.57 ± 0.12
NGC 4234	13.15 ± 0.10
NGC 4630	12.84 ± 0.20
NGC 4633	13.33 ± 0.11
IC 3258	13.52 ± 0.14
IC 3521	13.69 ± 0.13
IC 3665	14.53 ± 0.20
IC 3073	14.68 ± 0.20

CHAPTER 9

SOME QUESTIONS TO ANSWER BEFORE CALCULATING A DISTANCE SCALE

Are Virgo Galaxies Normal?

If the environment of the Virgo cluster has modified the diameters or magnitudes of the Virgo spirals, then the comparisons in this paper are harder to justify. This problem was reviewed by Sandage and Tammann (1976b), mainly with reference to the sizes of HII regions, total luminosities, and luminosity classifications of Virgo spirals. It was concluded that the Virgo spirals are not abnormal in total luminosity, do not have obviously decreased star formation, and do not have abnormal luminosity class assignments compared with their 21-cm linewidths.

More recent studies fall roughly into two categories; work involving the effects of cluster environments in general, and work specifically on the Virgo cluster. Dressler (1980) studied 55 rich clusters, not including Virgo, and firmly established that elliptical and S0 populations increase while spiral population decreases with increasing galaxy density. His figures 14, 15, and 16 suggest that the bulge magnitude of spirals decreases

with increasing density, that the disk-to-bulge ratio decreases with increasing density, and that the brightest spirals are underrepresented in low-density regions. A reanalysis of Dressler's data by Kent (1981) shows that these differences result from a systematic decrease in disk brightness with increasing density. This is attributed to disruption of the disks during the collapse of the cluster, but the relation between disk properties and density is too weak to be explained by tidal stripping.

Using his own data for nine clusters, Bothun (1982) found that spiral galaxies exhibit such a wide range in their global properties that they cannot easily be assigned to morphological bins. He concluded that initial conditions in galaxy formation, variations in star formation, and the amount of HI remaining after bulge star formation is complete are more important than environmental influences in determining the presently-observed properties of spirals in clusters.

Observations of HI in Virgo galaxies by Davies and Lewis (1973), Huchtmeier et al. (1976), Chamaraux et al. (1980), and Giovanardi et al. (1983) have firmly established that spirals within 6^{o} of the cluster center have hydrogen-mass-to-blue-light ratios which are lower than those of galaxies of the same types beyond the 6^{o} circle or in the field. The surface density of hydrogen

is nearly the same inside and outside of the cluster core, but the ratio of HI diameter (defined in terms of a scale length) to optical diameter is significantly larger outside the cluster core (Giovanelli and Haynes 1983). This implies that gas has been stripped from the outer disks of spirals in the core.

Giovanelli and Haynes (1983) derived an effective HI diameter, within which seventy percent of the HI emission is found. They compared this diameter with the Holmberg diameter to derive a distance-independent ratio. Comparing 19 spirals within 5^{o} of the center of the Virgo cluster to more than 50 galaxies outside the 5^{o} circle, they found that at constant luminosity the Virgo HI disks are smaller than the field disks.

Optical work by Kennicutt (1983) showed that the spirals within 6^{o} of the center of the Virgo cluster are redder than field galaxies by about 0.1 magnitude in B-V, but that the difference in the luminosity functions between Virgo and the field is probably insignificant. The equivalent width of the Hβ+[NII] blend in Virgo spirals (including disk and nucleus) is, on average, lower than in field galaxies, although the distribution of equivalent width versus galaxy type is very broad. This was taken to represent a real difference in the current star formation rate between Virgo and the field. Kennicutt concluded that there is a real difference

between Virgo spirals and their field counterparts at the same Hubble type, so that, for instance, a typical Sc galaxy in Virgo resembles a typical Sb-Sbc field galaxy in color, hydrogen-mass-to-blue-light ratio, and $H\beta$ equivalent width, so there is an inconsistency between a Virgo spiral's Hubble type and its gaseous and stellar content. To put it another way, the colors of the Virgo spirals are normal relative to field galaxies of the same HI content if Hubble type is ignored. A study of $H\beta$+[NII] equivalent width in galactic nuclei by Stauffer (1983) showed that Virgo nuclei are not significantly different from the nuclei of field galaxies. This was taken to show that whatever causes the depletion of Virgo disks is not strong enough to affect the nuclei.

Peterson, Strom, and Strom (1979) compared the radius-luminosity relations for Virgo and the Hercules cluster, and found the Virgo galaxies are about twelve percent smaller than the Hercules galaxies at the same luminosity. An allowance for Local Group motion toward Virgo would reduce the difference, but not eliminate it.

These sets of observations show the Virgo spirals are red and HI poor relative to field galaxies, and other properties may be slightly different as well. The differences seem to be primarily in the disks, suggesting that the modifying force is not strong enough to reach the nucleus. The most likely explanation is that the cluster

environment has enough influence to modify the disk properties. Galaxies which have had their HI content reduced may be smaller than field galaxies when diameters are measured in blue light, but there are no compelling data which indicate that they are fainter than field galaxies. In the end, abnormality or normality is difficult to establish without previous knowledge of the distance scale--knowledge detailed enough that the distance of each individual galaxy, in Virgo and the field, could be calculated. A precise definition of a normal galaxy would also be needed, but spiral galaxies, like people, are a population of individuals, each unique, so a normal value of any attribute is difficult to interpret.

For the purposes of this paper it is assumed that the Virgo spirals are at least normal enough to compare with the Local Group, in the hope that this will provide one more step in a bootstrap process of improving understanding of the distance scale. This assumption would probably be easier to justify if the comparisons were made with red light instead of blue, because the properties of a galaxy in blue light are so sensitive to star formation history, but reliable data in the red are in short supply. Due to this limitation, blue light must be used, but the errors due to this choice may be minimized by comparing the Local Group galaxies with

spirals from the less-dense parts of the Virgo cluster when this is possible. In this sense, NGC 4569 is a poor choice for the largest, brightest Virgo galaxy because it may be at the cluster center. NGC 4321, which is much farther from the center, should be more representative. Typical small, faint galaxies are taken from all over the cluster, and there are so many of them that a problem with one galaxy is of much less concern.

Are the Virgo Galaxies the Right Size and Brightness for Comparison?

Are the brightest (largest) Virgo galaxies brighter (larger) than M31, and are the faintest (smallest) Virgo galaxies fainter (smaller) than M33? These questions must be answered if the comparisons are to be successful, but the data are again difficult to interpret. Starting with magnitudes, several studies specify luminosity functions of galaxies. The analytical work of Schechter (1976) and Schechter and Press (1976) shows that the larger the cluster the more very bright and very faint galaxies the cluster contains. Thus, a large cluster, like Virgo, should have several galaxies brighter than the brightest member of a small cluster such as the Local Group, and several members fainter than the faintest member of the Local Group. This function does not give specific information on spirals.

Observations of cluster galaxies by Sandage (1976) show that the absolute magnitude of first-ranked E and S0 galaxies depends only weakly on cluster richness, but the absolute magnitude of second-ranked and third-ranked cluster galaxies shows a much stronger dependence, even for clusters with as few as four members. These results are confirmed by Godwin and Peach (1979). Similar observations summarized by Sandage and Tammann (1976b) conclude that E, Sb, and Sc galaxies reach nearly the same upper luminosity, but the mean luminosity of the spirals is lower than the mean luminosity of ellipticals. This suggests that the larger the cluster the more likely it is to contain a very bright spiral.

A study of the magnitudes and Hubble types of Virgo spirals by Strom (1980) shows that late-type spirals persist to fainter absolute magnitudes than early-type spirals, and, with less certainty, that the average absolute magnitude for spirals of a given Hubble type gets fainter as one considers later types. This means that the brightest Virgo spirals could be of any Hubble type, but the faintest Virgo spirals are likely to be of late Hubble types. It also suggests that M33, of Hubble type Sc and a the faintest spiral in the Local Group, is brighter than the faintest Scd and Sd galaxies in Virgo.

Finally, M33 is as bright or brighter than the dwarf galaxies in the Local Group, and it is expected to be

brighter than dwarf galaxies in Virgo. The recent list of dwarf galaxies in Virgo by Reaves (1983) provides many galaxies assumed to be Virgo members on the basis of their distribution. Twenty-two of these have B_T magnitudes and D_{25} diameters in the catalog of de Vaucouleurs and Pence (1979), so M33 can be compared with them. It must be noted that these galaxies are likely to be the dwarfs of highest surface brightness and possibly the brightest dwarfs in the cluster. Thus, the comparison is not between M33 and some sort of average dwarf galaxy, but between M33 and the smallest, faintest dwarf galaxies with reliable data.

Studies which define a diameter distribution function of galaxies are very rare. There is nothing like a Schechter function for diameters to help the present analysis. It still is likely, however, that a cluster as large as Virgo should have more very large galaxies and more very small galaxies than a small cluster like the Local Group.

The data adopted for the comparisons do give some confirmation that the range of magnitudes and diameters of the Virgo galaxies is suitable for the comparison with Local Group galaxies. For a reliable comparison the difference in apparent magnitude between the brightest and faintest Virgo spirals must be greater than the difference in absolute magnitude between M31 and M33. A similar

inequality must hold for the difference in the log of the angular diameter. If the difference in Virgo is greater than the difference in the Local Group it assures that the Virgo galaxies are brighter (larger) or fainter (smaller) than the Local Group galaxies, or both, so at least one of the limits to the distance scale calculated in the comparison is a strong one. These differences have been calculated for several pairs of Virgo galaxies and for M31 and M33 in the Local Group. The results are given in the next chapter. Here it is only noted that in each case the difference is larger in Virgo.

CHAPTER 10

COMPARISON WITH THE VIRGO CLUSTER

Overview

The results of the calculations, given as limits to the distance modulus of the Virgo cluster in the RC2 system, are in Tables 8 and 9. The results in other data systems may be found in Appendix B. The smallest distance modulus in the RC2 system is 30.29 from comparing the magnitudes of M31 and NGC 4569. The largest distance modulus is 33.10, from comparing the magnitudes of M33 and IC 3073.

Of all systems the smallest distance modulus is 30.13 from comparing M31 and NGC 4569 using the Holmberg magnitudes with the corrections of Sandage and Tammann (1976b). The largest distance modulus is 33.28 from comparing the magnitudes of M33 and IC 3073 in the RC2 system under the assumption that the Milky Way absorption is zero.

The strongest trend in the results is their similarity across the available data and correction systems. In general the RC2, RSA, and Holmberg systems give remarkable agreement, with two exceptions. First,

Table 8. Lower limits to the distance modulus of Virgo cluster galaxies in the RC2 system.

	Comparison	
Galaxy	Diameters	Magnitudes
NGC 4569	30.38 ± 0.25	30.29 ± 0.19
NGC 4321	30.80 ± 0.24	30.37 ± 0.18
NGC 4303	---	30.48 ± 0.18
NGC 4517	30.75 ± 0.33	---
NGC 4192	30.59 ± 0.28	---

Table 9. Upper limits to the distance modulus of Virgo cluster galaxies in the RC2 system.

	Comparison	
Galaxy	Diameters	Magnitudes
NGC 4299	31.81 ± 0.23	31.06 ± 0.16
NGC 4234	32.45 ± 0.25	31.56 ± 0.14
NGC 4630	31.99 ± 0.23	31.25 ± 0.22
NGC 4633	31.78 ± 0.25	31.74 ± 0.15
IC 3258	31.99 ± 0.28	31.92 ± 0.17
IC 3521	32.74 ± 0.29	32.10 ± 0.16
IC 3665	32.96 ± 0.29	32.94 ± 0.22
IC 3073	32.90 ± 0.29	33.10 ± 0.23

the lower limits calculated using the RSA value for the magnitude of M31 are all much larger than the limits calculated in the other systems. This suggests that the RSA magnitude of M31 is too bright, or that the magnitudes of M31 in all the other systems are all too faint. The results using the recalculated RSA magnitude, 3.13, are closer to the results in the other systems, so it is likely that A_B for M31 in the RSA is too high by about 0.3

magnitude, (as explained in Chapter 8). Researchers using the RSA magnitude for M31 in further calculations should be aware of this possible inaccuracy. The second disagreement results from using Holmberg's diameter for M31 in the upper limit calculations. The resulting distance moduli are smaller than those calculated in the other systems, suggesting the Holmberg diameter is too small. This is in agreement with remeasurements by de Vaucouleurs (1958) and by Hodge and Kennicutt (1982). The remarkably good agreement among the systems may be due partly to the fact that the basic catalogs are not independent, for Holmberg's data were often transformed to the RC2 system, and the raw B magnitudes in the RC2 and RSA are usually identical.

The results in the RC2 system in this chapter, combined with the results in Appendix B, include three different values of A_B; A_B = 0.20 magnitude from the RC2, A_B = 0 as in the RSA and HHV, and A values calculated for each individual galaxy by Burstein and Heiles (1984). The results point out the importance of settling the dispute over Milky Way absorption, for the difference between A_B = 0 and A_B = 0.20 results in a difference of 0.20 in the distance moduli calculated from magnitudes and 0.10 in the moduli from diameters of small galaxies, but less for large galaxies. Results using the Burstein and Heiles values of the absorption tend to split the difference

between the RC2 results and $A_B = 0$ results, or come close to the RC2 results. The Virgo cluster is an important rung in the ladder of the extragalactic distance scale, and such an obvious source of debate over its distance modulus should not be left unresolved.

Adopted Limits to the Virgo Distance Modulus

The lower limit to the Virgo distance modulus is the easier to determine, for the cluster membership lists show reasonable agreement over which bright, large galaxies are members. If NGC 4569 is a member, the lower limit from the magnitude comparison is 30.4 ± 0.2, determined by simply looking at the tabulated values (but eliminating the comparison which uses 2.71 as the RSA magnitude of M31). This value is not calculated by finding a mean from the table because the individual results are not independent. For instance, the errors across a row or down a column are certainly correlated, and taking a simple mean would be equivalent to giving greatest weight to the data system with the most correction schemes, even though the different correction schemes arise from uncertainty in the data system. If the uncertainty over the membership of NGC 4569 is taken to be a serious drawback, then the lower limit to the distance modulus is 30.6 ± 0.2 taking 4321 or NGC 4303 as the brightest member.

Limits from diameters, determined in a similar fashion, are 30.5 ± 0.2 for NGC 4569, 30.7 ± 0.2 for NGC 4517 and NGC 4192, and 30.8 ± 0.2 for NGC 4321. It is comforting to find that the two limits calculated with the magnitudes and diameters of NGC 4569 and NGC 4321 are so consistent. This does not hold for all galaxies, for instance the lower limit using the magnitude of NGC 4303 would be 31.1 ± 0.2, a difference of more than half a magnitude from the limit calculated with diameters. These differences are an indication that the relationship between magnitudes and diameters is a broad one. From these limits reasonable lower limits to the Virgo distance modulus are 30.5 ± 0.2 if NGC 4569 is a member, and 30.7 ± 0.2 if it is not. These limits are firm, for if the modulus is smaller then, M31 is intrinsically brighter and larger than all the spirals in Virgo, an unacceptable result.

Arriving at an upper limit to the Virgo modulus is more difficult for at least three reasons; the membership of individual faint, small galaxies is much less certain, the data for faint galaxies are much less certain, and it is not clear how to choose a list of Virgo galaxies which are definitely fainter and smaller than M33, but not so much fainter and smaller that the comparison becomes absurd. Only new, more extensive observations can solve the first two problems, but some headway can be made on

the third problem by considering the differences in magnitudes and diameters between pairs of galaxies in the Local Group and Virgo. To the author's knowledge this is the first time such a comparison has been used for testing galaxy samples in a distance scale calculation.

Calculate the difference in absolute magnitudes between M31 and M33 in the Local Group and the difference in apparent magnitude between the brightest and faintest galaxies in the Virgo cluster. Do the same with the angular diameters of M31 and M33 in the Local Group and the largest and smallest galaxies in the Virgo cluster. The RC2 data must be used for this comparison, for it (and its extension by de Vaucouleurs and Pence 1979) is the only catalog with data on the faint galaxies. If the differences are greater in Virgo than in the Local Group then, certainly, one of the limits to the distance scale is firm, and it becomes more likely that both are firm. This analysis is complicated by the observation that for each individual galaxy used in calculating the upper limit distance moduli there is little agreement between the results from magnitudes and from diameters. The modulus from magnitudes is several tenths of a magnitude greater than the modulus from diameters for almost all galaxies. This may mean that either M33 or most of the Virgo galaxies has an unusual magnitude-diameter relationship. Of the two the former is considered more likely.

The difference in absolute magnitudes between M31 and M33 is 2.10 ± 0.20, while the difference in corrected apparent magnitude between NGC 4321 and NGC 4299 is 2.70 ± 0.14. This difference is not large enough to assure both that NGC 4321 is brighter than M31 and NGC 4299 is fainter than M33. The difference for NGC 4321 and NGC 4633 is 3.47 ± 0.13, and this is taken to be more than large enough to assure that both magnitude conditions are met. The difference between the magnitudes of NGC 4321 and IC 3521 is 3.83 ± 0.15, making it exceedingly likely that the two magnitude conditions are met, and the difference between NGC 4321 and IC 3665 is 4.67 ± 0.22, ridiculously large. If NGC 4321 is intrinsically 1.0 magnitude brighter than M31, making NGC 4321 an exceptionally bright spiral, then IC 3665 would be intrinsically 1.57 magnitude fainter than M33, making IC 3665 an exceedingly faint galaxy. Comparing M33 with IC 3665 gives an upper limit to the Virgo modulus of 32.94 ± 0.23, a ridiculously large value.

The difference in $\log D_0$ between M31 and M33 is 0.42 ± 0.04. The difference between NGC 4321 and NGC 4299 is 0.60 ± 0.05, and the difference between NGC 4321 and NGC 4633 is 0.60 ± 0.05, both giving about fifty-five percent greater difference for the Virgo pair. Because M31 is usually considered to be a very large galaxy, so that it is unlikely a normal Virgo galaxy could be much

larger, this difference is assumed to be large enough to guarantee that NGC 4321 is larger than M31 and the small Virgo galaxy is smaller than M33. This gives an upper limit to the Virgo modulus of 31.8 ± 0.2. Other reliable comparisons involve M33 and NGC 4234, IC 3521, and IC 3665. Respectively, the differences in log D_0 between NGC 4321 and these galaxies are 0.73 ± 0.05, 0.79 ± 0.06, and 0.84 ± 0.06, all showing the linear diameter range between the Virgo pair to be more than double that of the Local Group pair. The respective limits to the distance moduli are 32.45 ± 0.25, 32.74 ± 0.29, and 32.96 ± 0.29. The last two, in particular, seem unreasonably large.

The adopted limit to the Virgo modulus depends strongly on the faintest, smallest Virgo galaxies chosen for comparison. The dwarf galaxy IC 3665 gives 32.95 ± 0.3 as an upper limit, while the Sd galaxy NGC 4633 gives 31.76 ± 0.2, and galaxies such as NGC 4234 and IC 3521 give intermediate results of 32.0 ± 0.5 and 32.5 ± 0.3. The strength of these limits is again shown by considering the consequences if the Virgo modulus is greater than the calculated limit, for then M33 would be fainter and smaller than the designated Virgo galaxies.

Implied Limits to Hubble's Constant in the Direction of Virgo

The adopted distance moduli may now be used to calculate limits to the value of Hubble's constant for the Virgo cluster, using equation (3) from Chapter 2 and the adopted Virgo cluster radial velocities from Chapter 3. The resulting limits in the RC2 system are shown in Tables 10 through 13. (At least fifty more tables would be necessary to include all the results from other systems. They do not give significantly different results, so they are not included. Readers are encouraged to use the data in Appendix B to calculate any other limits which interest them.) Each table has two columns of results, one for V = 1100 ± 100 km/s, and one for V = 1500 ± 100 km/s, reflecting the disagreement over the radial velocity of the Virgo cluster. If V = 1100 km/s is correct, then the upper limit to H is 94 ± 10 km/(s*Mpc) if NGC 4569 is taken to be the largest, brightest Virgo spiral, and 84 ± 9 km/(s*Mpc) if NGC 4321 is the largest and brightest. Neither of these limits conflicts with recent determinations of H for Virgo in which V is taken to be in the neighborhood of 1100 km/s, but it is close to the value H ~ 80 km/(s*Mpc) in the Virgo direction found by de Vaucouleurs and Bollinger (1979) in which V ~ 1500. If V is taken to be 1500, the corresponding results of the limit calculations are 128 ± 10 km/(s*Mpc) and

Table 10. Upper limits to H in the RC2 system from the diameters of the largest Virgo cluster galaxies.

	Assumed radial velocity	
Galaxy	1100 km/s	1500 km/s
NGC 4569	92.3 ± 9.6	125.8 ± 10.5
NGC 4321	76.2 ± 7.9	103.9 ± 8.6
NGC 4517	77.8 ± 8.7	106.1 ± 9.9
NGC 4192	83.9 ± 8.9	114.4 ± 9.9

Table 11. Upper limits to H in the RC2 system from the magnitudes of the brightest Virgo cluster galaxies.

	Assumed radial velocity	
Galaxy	1100 km/s	1500 km/s
NGC 4569	96.1 ± 9.5	131.3 ± 10.1
NGC 4321	92.6 ± 9.0	126.4 ± 9.6
NGC 4303	88.1 ± 8.6	120.3 ± 9.1

Table 12. Lower limits to H in the RC2 system from the diameters of the smallest Virgo cluster galaxies.

	Assumed radial velocity	
Galaxy	1100 km/s	1500 km/s
NGC 4299	47.8 ± 4.9	65.1 ± 5.2
NGC 4234	35.6 ± 3.7	48.6 ± 4.1
NGC 4630	44.0 ± 4.5	60.0 ± 4.9
NGC 4633	48.4 ± 5.0	66.1 ± 5.5
IC 3258	44.0 ± 4.7	59.9 ± 5.3
IC 3521	31.1 ± 3.4	42.5 ± 3.8
IC 3665	28.1 ± 3.0	38.3 ± 3.4
IC 3073	28.9 ± 3.1	39.4 ± 3.5

Table 13. Lower limits to H in the RC2 system from the magnitudes of the faintest Virgo cluster galaxies.

Galaxy	Assumed radial velocity	
	1100 km/s	1500 km/s
NGC 4299	67.4 ± 6.5	91.9 ± 6.8
NGC 4234	53.6 ± 5.1	73.1 ± 5.3
NGC 4630	61.9 ± 6.3	84.5 ± 6.8
NGC 4633	49.4 ± 4.7	67.4 ± 4.9
IC 3258	45.2 ± 4.4	61.7 ± 4.6
IC 3521	41.9 ± 4.0	57.1 ± 4.2
IC 3665	28.4 ± 2.9	38.7 ± 3.1
IC 3073	26.5 ± 2.7	36.2 ± 2.9

114 ± 9 km/(s*Mpc), which do not conflict with any recent determinations of H in the Virgo direction.

If V = 1100 ± 100 km/s the lower limits to H are 49 ± 5 km/(s*Mpc), 44 ± 4, 36 ± 4, and 28 ± 3 for NGC 4633, NGC 4234, IC 3521, and IC 3665 respectively. If V = 1500 ± 100 km/s the corresponding results are 66 ± 5 km/(s*Mpc), 59 ± 5, 50 ± 4, and 38 ± 3. If V = 1500 is correct then values of H near 50 km/(s*Mpc) are made unacceptably small by these limits.

The tables also show that calculating H using a pair of well-observed galaxies, such as one from the Local Group and one from the Virgo cluster, results in an uncertainty of at least ten percent. This is likely to be the lowest possible uncertainty in comparing the diameters or magnitudes of a single pair of galaxies, because few galaxies have been observed to the same accuracy as have

M31, M33, and the Virgo spirals. This means distance scale calculations using pairs of galaxies, such as brightest cluster members, will always have at least this much uncertainty.

The lower limit calculations give a range of values for H depending on the faint, small galaxy chosen for comparison. There is a wide range of choices, so several galaxies are included in the table in the hope of providing an acceptable galaxy for all readers.

Only limits to H are calculated in this paper, not a value of H, but Figures 2 and 3 show where M31 and M33 would fall in the Virgo magnitude and diameter distributions if they were placed at various distance moduli, μ, corresponding to possible distances of the Virgo cluster. The histogram is plotted by taking all the Virgo galaxies in the list of Geller and Huchra (1983) to be members. Values of B_T^0 and log D_{25} are taken directly from the RC2 without modification, because it is simply too time consuming to calculate diameters and magnitudes for each data set and correction scheme. The histograms show that if $\mu > 32.0$ then M31 is very modest in size and brightness, and M33 is an exceedingly small galaxy or a dwarf. If $\mu < 30.5$, M31 is exceedingly large and bright, and M33 is brighter and larger than the galaxies at the peaks of the distributions. If $\mu = 31.0$, then M31 is in the middle of the large, bright extensions of the

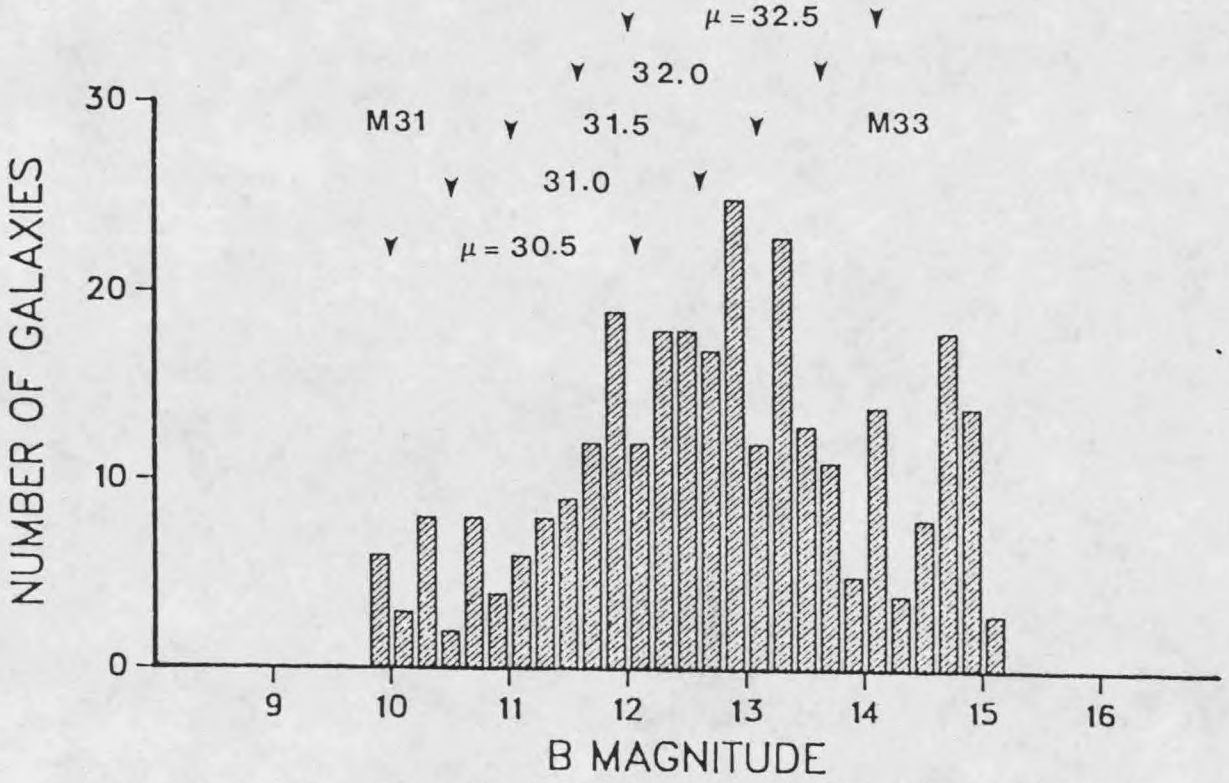


Figure 2. Magnitude histogram of the Virgo cluster.

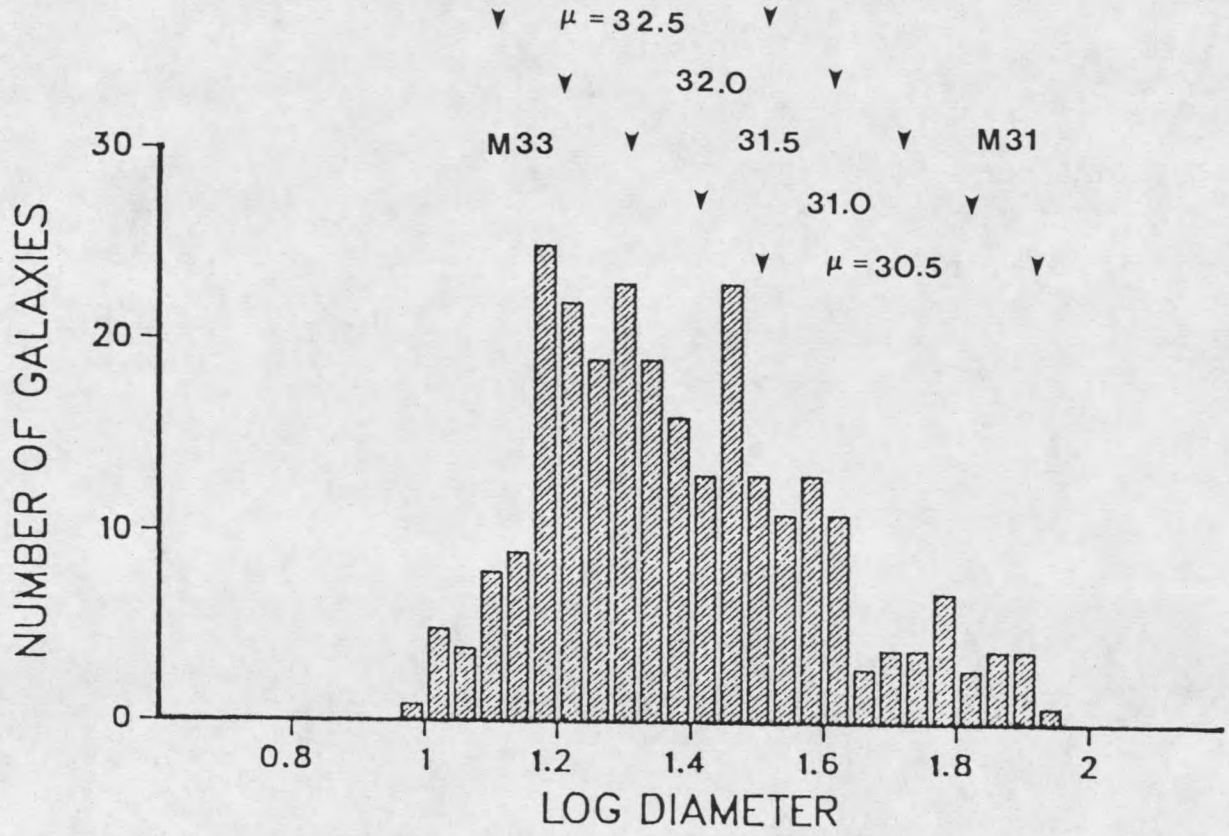


Figure 3. Diameter histogram of the Virgo cluster.

distributions, making it a typical large, bright galaxy, and M33 is near the peaks of the distributions, making it an ordinary spiral.

The histograms also show that the distributions of normal Virgo spirals seem to cut off at $B_T^0 = 13.8$ and $\log D_{25} = 1.16$. It is tempting to take these as lower limits for normal spirals which are Virgo members. Comparison with M33 then gives moduli of 32.21 from magnitudes and 32.20 from diameters, so close that the difference is negligible. This gives $H > 40$ if $V = 1100$, and $H > 54$ if $V = 1500$. Before taking these as firm lower limits it must be established that the cutoffs are an intrinsic property of the cluster and not a property of the catalogs. This cannot be done until more radial velocities are available for faint galaxies in the Virgo region so their membership can be established.

The magnitude histogram also shows a remarkable decrease at $B_T^0 = 13.0$ with an increase at 13.2. This may simply be due to the statistics of small numbers, and until the Virgo cluster is better observed and membership defined no conclusions can be drawn.

Finally, both histograms show long, low extensions for the large, bright galaxies. The magnitude extension runs from B_T^0 values of 11.4 to 9.8, and the diameter extension from $\log D_{25}$ values of 1.64 to 1.96. These extensions emphasize that large, bright galaxies are rare.

CHAPTER 11

COMPARISON WITH THE URSA MAJOR CLUSTER

After Virgo, the most populous gathering of galaxies is in the Ursa Major region. As difficult as it was to find an acceptable sample of galaxies and reliable data in Virgo, it is more difficult in Ursa Major, for no reviews of Ursa Major cluster properties have appeared in the literature.

The Sample

Geller and Huchra (1983) have published the largest membership list in the Ursa Major region, giving 170 galaxies which are likely members. Their list is a merger of the Ursa Major, Coma, and Canes Venatici clusters. Many other authors, including Turner and Gott (1976) and de Vaucouleurs (1975), hold these to be associated but distinct clusters.

The largest and brightest spiral in the Ursa Major cluster is NGC 4258, according to Geller and Huchra, but Turner and Gott list it as a member of their group 50, with an average radial velocity of 311 km/s, too low for the present distance scale calculation. It is assigned to the nearby Canes Venatici I group by de Vaucouleurs. The

next largest and brightest in the list of Geller and Huchra is NGC 4736, which is listed as a field galaxy (that is, not belonging to any cluster) by Turner and Gott. They note it could be a member of one of the clusters in the region, but do not specify which one.

The next in the list of Geller and Huchra is NGC 4631, which is taken as a member of the nearby Canes Venatici II cloud by de Vaucouleurs. The next two galaxies, NGC 4565 and NGC 4725, are much too far south to be members of Ursa Major. They are taken as members of the Coma region by Turner and Gott and by de Vaucouleurs. The next largest and brightest spiral is NGC 4244. Turner and Gott find 4244 is a field galaxy, and it seems to be too far south to be a member of Ursa Major. The same holds for the next galaxy, NGC 4559. De Vaucouleurs lists 4244 as a probable member of the Canes Venatici I cloud, and 4559 as a member of the Coma cloud.

The next two largest and brightest galaxies from the list of Geller and Huchra are NGC 3718, which is accepted as a member of Ursa Major in all the lists, and NGC 3992, which Turner and Gott list as a field galaxy associated with the cluster. These two will be adopted as the largest, brightest members for the present calculations. If it is possible, the choice of small, faint galaxies for comparison is even more difficult, this time because of lack of data. The smallest, faintest galaxy which appears

in all the membership lists (Geller and Huchra 1983, Turner and Gott 1976, and de Vaucouleurs 1975) and which has both a magnitude and diameter in the RC2 is NGC 3683. Its status in Ursa Major is similar to the status of NGC 4299 in Virgo; neither is especially faint or small, but each is the faintest, smallest unanimously accepted member with good data. To improve the comparison, NGC 3499 will also be included. It has the correct direction and radial velocity to be a member, but is too faint to be considered for membership by Turner and Gott. Unfortunately, it has only a diameter in the RC2, so it cannot be used in the magnitude comparisons.

Data

The angular diameters and magnitudes listed in Table 14 come from the RC2. The log D_0 and B_T^0 values have been recalculated in order to propagate the errors, and except for roundoff differences the values agree with those listed in the RC2. Other data systems will not be used because it has already been shown there is little difference among the systems.

The Ursa Major membership lists also give average radial velocities, but the value depends on the sample. Turner and Gott (1976) find an average radial velocity of 1762 km/s, but their list includes some high-velocity galaxies not included in other lists. Geller and Huchra

Table 14. Data in the RC2 system for Ursa Major cluster galaxies.

Galaxy	log D	Magnitude
NGC 3718	1.90 ± 0.04	10.80 ± 0.13
NGC 3992	1.86 ± 0.03	10.22 ± 0.11
NGC 3683	1.23 ± 0.05	12.87 ± 0.17
NGC 3499	1.01 ± 0.04	---

(1983) find an average velocity of 1395 km/s, which transforms to 1122 km/s when their correction for Local Group motion is removed. Their membership list is a merger of the Ursa Major, Coma, and Canes Venatici clusters, and this may change the calculated velocity. The Ursa Major cluster has not been studied as much as the Virgo cluster, so there are no other large membership lists with radial velocity determinations to settle this disagreement. The incomplete radial velocity data of de Vaucouleurs (1975) favor the lower value. Because of this there is no simple way to decide which velocity is correct, so both will be kept. The error for each velocity is assumed to be 100 km/s, the same as the error in the Virgo velocity.

Results and Discussion

The results of the comparisons are given in Table 15 as limits to the distance modulus of the Ursa Major cluster, and in Tables 16 and 17 as limits to Hubble's

Table 15. Limits to the distance moduli of Ursa Major cluster galaxies in the RC2 system.

Galaxy	Type of comparison	
	Diameters	Magnitudes
NGC 3718	30.54 ± 0.28	31.31 ± 0.21
NGC 3992	30.74 ± 0.26	30.73 ± 0.19
NGC 3683	31.87 ± 0.27	31.28 ± 0.20
NGC 3499	32.96 ± 0.24	---

Table 16. Limits to H in the RC2 system from diameters of Ursa Major cluster galaxies.

Galaxy	Assumed radial velocity	
	1122 km/s	1762 km/s
NGC 3718	87.4 ± 9.2	137.3 ± 11.0
NGC 3992	79.5 ± 8.2	124.9 ± 9.6
NGC 3683	47.3 ± 4.9	74.3 ± 5.8
NGC 3499	28.7 ± 2.9	45.1 ± 3.3

Table 17. Limits to H in the RC2 system from magnitudes of Ursa Major cluster galaxies.

Galaxy	Assumed radial velocity	
	1122 km/s	1762 km/s
NGC 3718	61.4 ± 6.0	96.7 ± 6.8
NGC 3992	80.1 ± 7.8	126.0 ± 8.7
NGC 3683	62.3 ± 6.1	97.9 ± 6.8

constant. The results are surprisingly similar to the results for the Virgo cluster. If the radial velocity of Ursa Major is 1122 km/s, the upper limit to H is 80 ± 8 km/(s*Mpc), excluding the result from the magnitude of NGC

3718. If the velocity is 1762 km/s, the upper limit to H is 130 ± 10 km/(s*Mpc), again excluding the result from the magnitude of NGC 3718. The lower limits to H are 30 ± 3 km/(s*Mpc) and 45 ± 3 km/(s*Mpc) for velocities of 1122 km/s and 1762 km/s respectively, using the diameter of NGC 3499. The lower limits to H calculated from the magnitude of NGC 3683 overlap the upper limits calculated from the magnitude of NGC 3718, but this is because NGC 3683 is not a faint galaxy. No claim is made that NGC 3683 should give a reliable limit, for too little is known about faint, small members of the Ursa Major cluster.

The similar results for the Ursa Major and Virgo clusters mean that if the Local Group has a component of motion toward Virgo, relative to a uniform Hubble flow, it has a similar component of motion toward Ursa Major. This makes sense, for the Virgo and Ursa Major clusters, as tabulated by Geller and Huchra (1983) have 248 and 170 members respectively, are less than forty degrees apart, and are approximately at the same distance. This is by far the largest concentration of mass near the Local Group. The gravitational force exerted by that mass on the Local Group should be directed toward a point between the clusters, so the Local Group would have nearly equal components of motion toward the two groups. This is in agreement with the known anisotropy of the the cosmic background radiation (Gorenstein and Smoot 1981).

CHAPTER 12

COMPARISONS WITH GROUPS SEEN IN PROJECTION BEHIND VIRGO AND URSA MAJOR

Essentially no researchers have used the groups of galaxies seen in projection behind the Virgo and Ursa Major clusters for distance scale calculations, but such calculations are valuable for two reasons. First, they can set limits on obscuring matter in the cluster and in the intergalactic space behind the cluster. If there is obscuring matter anywhere, it is expected to be concentrated in the gravitational wells of large clusters. Intergalactic matter would make galaxies in groups behind the clusters look dimmer and smaller. Equations (1) and (2) in Chapter 2 show that this would cause the distance modulus, μ, of the groups to be overestimated, so limits to H for the groups would be underestimated. Second, they can be used to find groups with a significant component of motion toward Virgo or Ursa Major. It is now well accepted that the Local Group has a component of motion of about 300 km/s roughly toward the Virgo cluster, and the Local Group is presently the only group known to have such a motion. This puts the Local Group in a unique reference frame, which the Cosmological Principle and special

relativity make unacceptable. If other groups can be found with components of motion toward clusters, then the Local Group is no longer in such a unique position. Such velocity components would not affect limits to distance moduli, but would affect limits to H. If the radial velocity of the group of galaxies relative to the Local Group is too large then the limit to H would be too large. If the velocity is too small, H would be too small.

In this chapter limits to the distance scale will be calculated using groups behind the large clusters. A group is taken to be a small assembly of galaxies, as compared with a cluster, which may have more than one hundred members. The Local Group is a typical small group, with three bright galaxies (M31, M33, and the Milky Way) and several dwarfs. Sandage (1976) and Godwin and Peach (1979) have shown that the absolute magnitude of the brightest galaxy in groups and clusters is nearly constant even for groups with as few as four members. This means the limit calculations remain valid even for comparing the Local Group with other small groups, but the analytical work of Schechter (1976) shows the uncertainty in the results is expected to increase.

Choice of Distant Groups for Comparison

The distant groups are selected from the list of Geller and Huchra (1983) with the requirements that the

group's brightest or largest member must be a spiral, the radial velocity of the group be greater than 700 km/s (greater than 1000 km/s in the catalog) and the position of the group must be within twenty degrees of one of the clusters. These requirements guarantee that the groups are seen in projection behind the clusters, and guarantee that if the groups have a component of motion toward the clusters it will be apparent from the Local Group. The Virgo and Ursa Major clusters are separated by only thirty-nine degrees, so galaxies which appear between them could be affected by both clusters. The groups which meet the requirements and their largest, brightest spiral galaxies are listed in Table 18. The NGC 4446 group is included from the work of Sulentic (1980).

Data

The magnitudes and diameters for this comparison are taken from the RC2, which is the only catalog with data on the faintest galaxies. Only the RC2 correction scheme is used, because it has been shown that the differences between the corrections do not greatly affect the final limits to the distance scale. The corrections have been recalculated to propagate the errors, so the values in Table 19 may differ from those in the RC2 by 0.01 in B_T^0 or in log D_0 due to roundoff. A dash in the table means data were not available to calculate that particular parameter.

Table 18. The largest, brightest galaxies and radial velocities of groups behind the Virgo and Ursa Major clusters.

G+H* Group	Group velocity	Galaxy
67	1675	NGC 3430
73	7390	NGC 3478
75	784	NGC 3675
78	913	NGC 3627
82	3590	A1122+64
82	3590	A1129+62
83	5788	NGC 3720
84	1872	NGC 3813
86	2639	NGC 3786
88	3302	NGC 3800
91	3314	NGC 3961
92	4166	NGC 3902
93	3163	NGC 3995
96	4171	A1202+18
97	980	NGC 4064
100	1331	NGC 4123
102	6414	NGC 4146
103	4041	NGC 4357
104	3207	NGC 4290
108	2815	NGC 4545
110	7597	NGC 4541
112	5052	NGC 4686
121	6937	NGC 5230
123	2519	NGC 5371
---	7500	NGC 4446

*Geller and Huchra (1983)

Table 19. Data in the RC2 system for the galaxies behind the Virgo and Ursa Major clusters.

Galaxy	log D	Magnitude
NGC 3430	1.55 ± 0.03	11.77 ± 0.11
NGC 3478	1.40 ± 0.04	12.48 ± 0.21
NGC 3675	1.73 ± 0.04	10.49 ± 0.17
NGC 3627	1.89 ± 0.03	11.27 ± 0.13
A1122+64	1.43 ± 0.04	---
A1129+62	1.17 ± 0.04	13.75 ± 0.16
NGC 3720	1.05 ± 0.05	13.67 ± 0.10
NGC 3813	1.31 ± 0.04	11.88 ± 0.11
NGC 3786	1.35 ± 0.03	---
NGC 3800	1.23 ± 0.05	---
NGC 3963	1.46 ± 0.03	12.09 ± 0.21
NGC 3902	1.26 ± 0.04	---
NGC 3995	1.36 ± 0.04	12.30 ± 0.14
A1202+18	1.09 ± 0.04	---
NGC 4064	1.59 ± 0.04	11.71 ± 0.17
NGC 4123	1.64 ± 0.03	11.54 ± 0.11
NGC 4146	1.21 ± 0.04	---
NGC 4357	1.51 ± 0.05	---
NGC 4290	1.39 ± 0.04	12.22 ± 0.21
NGC 4545	1.41 ± 0.04	---
NGC 4541	1.20 ± 0.04	---
NGC 4686	1.27 ± 0.05	---
NGC 5230	1.35 ± 0.04	12.46 ± 0.16
NGC 5371	1.64 ± 0.03	11.13 ± 0.08
NGC 4446	1.08 ± 0.05	14.19 ± 0.14

The radial velocities of the groups come from Geller and Huchra (1983), but their correction for the motion of the Local Group toward Virgo has been removed.

Results and Discussion

The results of the comparison are given in Table 20 and Figure 4. The figure shows radial velocity on the horizontal axis and upper limits to H on the vertical axis. (If a galaxy has two limits, one from diameters and

Table 20. Upper limits to H in the RC2 system for the galaxies behind the Virgo and Ursa Major clusters.

	Comparison	
Galaxy	Diameter	Magnitude
NGC 3430	59.3 ± 6.7	58.5 ± 6.3
NGC 3478	181.6 ± 21.1	186.0 ± 21.1
NGC 3675	41.5 ± 4.8	49.5 ± 5.4
NGC 3627	69.6 ± 7.9	40.1 ± 4.3
Al122+64	96.6 ± 11.1	---
Al129+62	52.6 ± 6.1	50.4 ± 5.5
NGC 3720	63.5 ± 7.5	84.5 ± 9.0
NGC 3813	38.2 ± 4.4	62.2 ± 6.7
NGC 3786	58.4 ± 6.6	---
NGC 3800	55.6 ± 6.7	---
NGC 3963	95.0 ± 10.8	100.2 ± 11.3
NGC 3902	74.3 ± 8.5	---
NGC 3995	71.9 ± 8.3	86.6 ± 9.4
Al202+18	51.5 ± 6.0	---
NGC 4064	37.4 ± 4.3	35.2 ± 3.9
NGC 4123	57.7 ± 6.5	51.6 ± 5.5
NGC 4146	103.3 ± 11.9	---
NGC 4357	127.8 ± 15.0	---
NGC 4290	78.7 ± 9.0	91.2 ± 10.3
NGC 4545	72.0 ± 8.3	---
NGC 4541	120.1 ± 14.0	---
NGC 4686	93.1 ± 11.1	---
NGC 5230	155.6 ± 17.7	176.4 ± 19.4
NGC 5371	108.3 ± 12.2	118.3 ± 12.6
NGC 4446	90.1 ± 10.8	86.2 ± 9.5

one from magnitudes, they are averaged to plot the value of H.) If the limit to H is distance-independent, as it should be if the Hubble flow is uniform and there is no intergalactic matter in the clusters, then the points in Figure 4 should scatter about the horizontal line which represents a reasonable upper limit to H, about 100 km/(s*Mpc). If there is uniformly-distributed

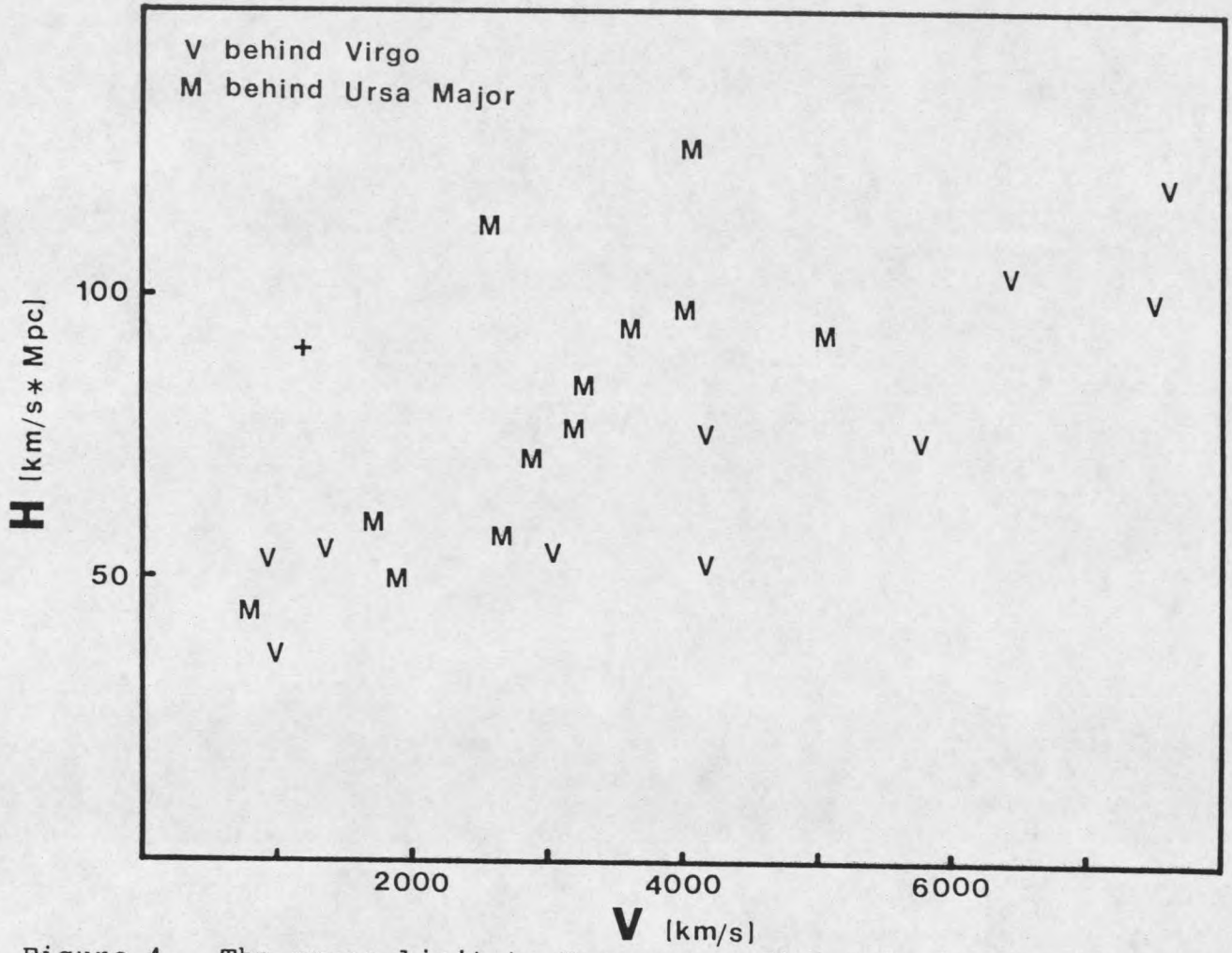


Figure 4. The upper limit to H versus radial velocity for the groups seen in projection behind Virgo and Ursa Major.

intergalactic obscuring matter then the points should scatter about a line of negative slope which would pass through the points defined by the Virgo and Ursa Major clusters (marked by a cross in the figure). If there is obscuring matter concentrated only in the clusters, then the points would scatter about a curve which has a step-function decrease at the Virgo and Ursa Major clusters, or at any other clusters which concentrate obscuring matter.

The points in the figure define a different line entirely. They scatter about a smooth curve which has positive slope, although the slope decreases as the radial velocity increases. Thus, to a radial velocity of about 8000 km/s there is no evidence for intergalactic matter, and no evidence for step-function discontinuities which would indicate inter-group concentrations of obscuring matter. The groups with radial velocities less than those of the Virgo and Ursa Major clusters also show that there is no step function at that velocity, so there is no concentration of obscuring matter in the clusters. It must be made clear that this sort of test is not sensitive to small amounts of obscuring matter. It could certainly detect one magnitude of total absorption in the most distant galaxies, but probably could not detect 0.3 magnitude.

It remains to explain the positive slope of the curve, which shows the surprising result that the distance dependence of H does not come from absorption. The most likely explanation is that the groups of galaxies feel the gravitational potential of the Virgo and Ursa Major cluster, so their radial velocities have been decreased relative to a uniform Hubble flow. This effect seems to extend as far as the clusters with radial velocities of about 3500 Km/s and seems to be equal for groups behind both of the clusters. This means that all the groups with $V < 3500$ seen in projection behind the Virgo and Ursa Major clusters have motion toward the clusters, relative to a uniform Hubble flow. Thus, the gravity of the clusters affects the motions of all groups within 2500 km/s in radial velocity (3500 - 1100 ~ 2500), or within 25 Megaparsecs in distance, taking $H_0 = 100$ km/(s*Mpc). Notice that the curve does seem to approach asymptotically an upper limit to H of about 100 or 110 km/(s*Mpc) at large radial velocities (large distances). This is consistent with the idea that at large enough distances from Virgo the effect of the cluster's gravitational well is small, smaller than the usual fluctuations about a uniform Hubble flow.

An unlikely explanation of the positive slope is that some force, whose magnitude is proportional to the distance from the clusters, acts to reduce the size and

brightness of all galaxies which are group members. This explanation is unacceptable because such a force would be acting on the Local Group as well as the other groups, restoring the slope to zero.

Another unlikely explanation of the positive slope is that all galaxies are attracted to the Local Group and the attraction depends on distance. This is unlikely because of the small mass of the Local Group. It is also unacceptable; it puts the Local Group in a preferred reference frame.

It is possible to test the explanations of the slope by calculating limits to H in the direction opposite to the Virgo cluster. If the Local Group and the other groups are affected by the gravitational potential well of the Virgo cluster then it is expected limits to H in the direction opposite Virgo should be higher than the results toward Virgo, especially for groups which are nearby. If the Local Group causes the curve, then the results in the direction opposite Virgo should be the same as the results toward Virgo. Actually, the results are already known to be higher--this has been shown by many authors, but the tables of de Vaucouleurs and Bollinger (1979) are particularly clear. It is not known if the results are found even for nearby groups, so the calculations are done here. The galaxies are chosen from the cluster lists of Geller and Huchra (1983) and Huchra and Geller (1982), and

must be within thirty degrees of the antipodal point of either cluster. No lower limit is placed on the radial velocity. The galaxies are listed in Table 21 and the limits to H in Table 22. The limits are plotted in Figure 5. The figure shows that for radial velocities less than 1500 km/s the values of H are much higher than in the direction toward the clusters (Figure 4). This is consistent with the idea that the groups are affected by the gravitational well of the clusters. The extent of the well, 2500 km/s in velocity relative to the clusters, or about 25 Mpc, is the same in both directions. Figure 5 also shows that the upper limits to H tend to about 100 km/(s*Mpc), the same as in Figure 4. This is further evidence that there is no detectable intergalactic obscuring material concentrated in the Virgo and Ursa Major clusters, for if obscuring matter was there the upper limit to H should be higher in the direction opposite Virgo.

In summary, Figures 4 and 5 provide the first evidence that many groups of galaxies around the Virgo and Ursa Major clusters have velocity components toward the clusters, relative to a uniform Hubble flow. The magnitude of the velocity depends on the distance between the group and the clusters, suggesting the gravitational well of the clusters is responsible for the velocity. The magnitude of the effect decreases to zero at a distance of

Table 21. The largest, brightest galaxies and radial velocities of groups antipodal to the Virgo and Ursa Major clusters.

Group*	Group velocity (km/s)	Galaxy
H 8	867	NGC 1291
H 12	1546	NGC 7582
H 15	1483	NGC 7424
H 17	1285	NGC 1365
H 24	3226	IC 1788
H 32	1514	NGC 1232
H 44	1418	NGC 1042
H 44	1418	NGC 1084
H 45	1893	NGC 615
H 47	4024	NGC 1417
H 48	1237	NGC 1068
H 52	2405	NGC 488
G172	3100	NGC 7757
G174	5439	NGC 7782
G 6	5020	NGC 173
G 6	5020	NGC 182
G 7	4523	NGC 245
G 7	4523	NGC 271
G 14	5428	NGC 521
G 17	875	NGC 628
G 21	1714	NGC 676
G 21	1714	NGC 718
G 23	5337	NGC 706
G 27	3755	IC 211
G 32	1295	NGC 1068
G 33	6750	NGC 1085
G 34	7449	NGC 1094
G 35	3082	IC 277

* G stands for Geller and Huchra (1983)
H stands for Huchra and Geller (1982)

Table 22. Upper limits to H in the RC2 system from galaxies antipodal to the Virgo and Ursa Major clusters.

Galaxy	Comparison	
	Diameters	Magnitudes
NGC 1291	92.1 ± 10.4	---
NGC 7582	62.4 ± 7.2	81.4 ± 8.8
NGC 7424	113.4 ± 12.7	85.9 ± 9.3
NGC 1365	113.7 ± 12.8	115.5 ± 12.4
IC 1788	68.5 ± 8.6	76.6 ± 8.3
NGC 1232	118.5 ± 13.4	108.5 ± 11.6
NGC 1042	65.9 ± 7.6	65.7 ± 7.1
NGC 1084	---	80.2 ± 8.6
NGC 615	64.5 ± 7.6	66.0 ± 7.2
NGC 1417	109.9 ± 12.8	113.6 ± 12.4
NGC 1068	86.8 ± 9.8	143.6 ± 15.2
NGC 488	123.6 ± 13.9	130.0 ± 13.8
NGC 7757	81.0 ± 9.3	---
NGC 7782	120.3 ± 13.8	127.7 ± 14.1
NGC 173	180.1 ± 20.8	---
NGC 182	115.6 ± 13.3	95.7 ± 10.5
NGC 245	---	93.8 ± 10.3
NGC 271	111.5 ± 12.9	---
NGC 521	186.9 ± 21.3	153.5 ± 16.8
NGC 628	91.3 ± 10.2	87.8 ± 9.3
NGC 676	60.4 ± 7.1	---
NGC 718	49.5 ± 5.7	49.1 ± 5.2
NGC 706	117.5 ± 13.5	---
IC 211	94.8 ± 10.9	---
NGC 1068	90.9 ± 10.3	150.4 ± 15.9
NGC 1085	117.3 ± 13.8	---
NGC 1094	108.8 ± 12.4	---
IC 277	48.2 ± 5.7	---

25 Mpc if H is 100 km/(s*Mpc). This is a first estimate of the range of the gravitational influence of the mass concentration associated with the Virgo and Ursa Major clusters.

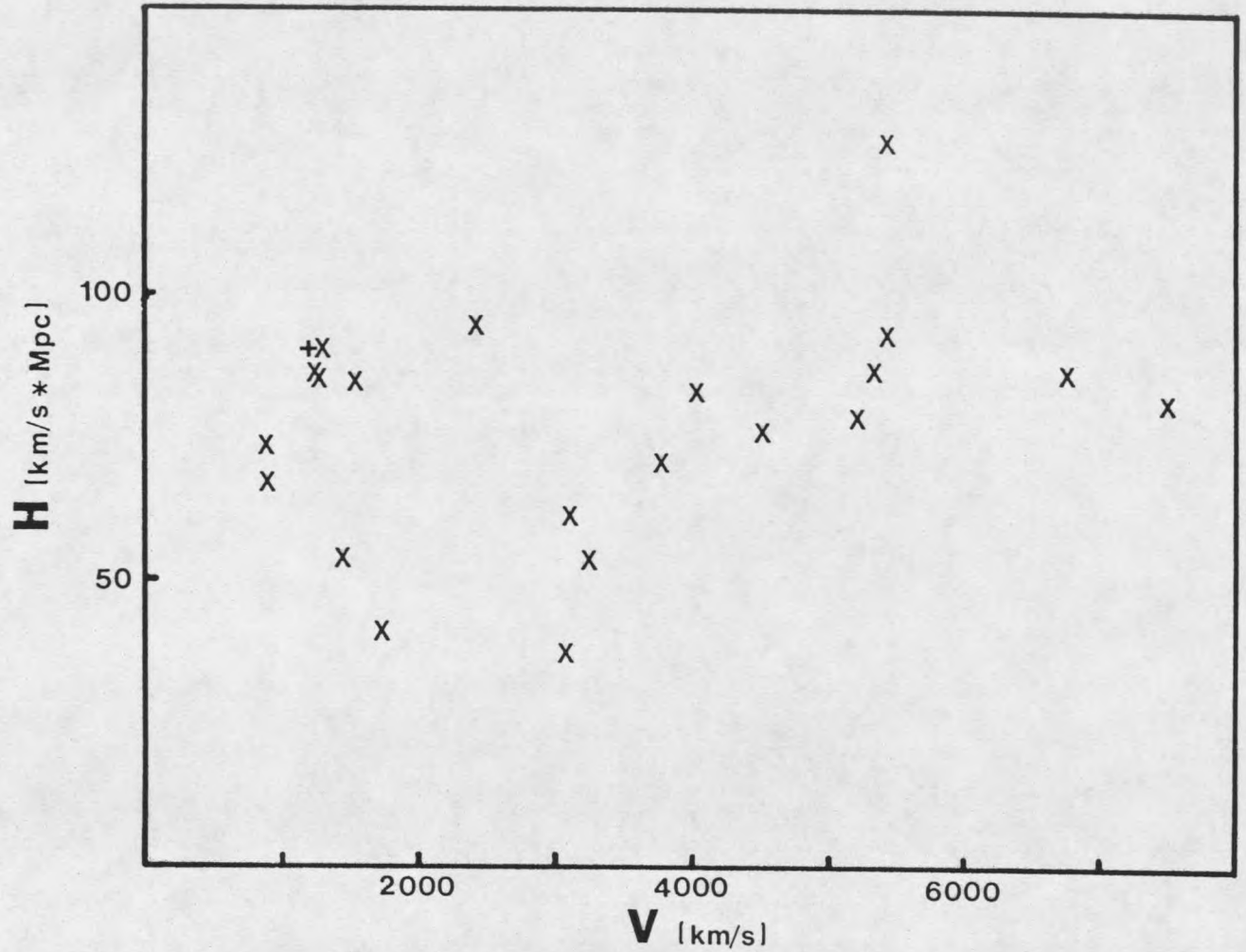


Figure 5. The upper limit to H versus radial velocity for the groups antipodal to Virgo and Ursa Major.

CHAPTER 13

CONCLUSIONS

Most of the conclusions have already been stated in the body of this thesis. They are gathered and stated succinctly here.

In this thesis limits to the extragalactic distance scale are calculated by assuming that M31, the largest, brightest galaxy in the Local Group, is the same intrinsic size and brightness as the largest, brightest galaxies in distant clusters. It is likely that the cluster galaxies are actually intrinsically larger and brighter than M31, so a lower limit to the distance scale results. This gives an upper limit to Hubble's constant.

Similarly, it is assumed that M33, the smallest, faintest galaxy in the Local Group, is intrinsically the same size as the smallest, faintest galaxies in distant clusters. It is likely that the cluster galaxies are actually intrinsically smaller and fainter than M33, so an upper limit to the distance scale results. This gives a lower limit to Hubble's constant.

It must be emphasized that there are unacceptable uncertainties in every step of the calculations of limits to the extragalactic distance, even though this is the

simplest method of calculation known. At present there is reasonable agreement on the values of the raw magnitudes and angular diameters, but the errors are often 0.1 in the magnitude and 0.05 in the log of the diameter, due to the difficulties in doing galaxy photometry. It is known that corrections to the raw data are necessary, but which corrections to apply, their size, and their functional forms are all in dispute. In particular, the Milky Way absorption at the galactic poles is uncertain by about 0.25 magnitude, and the existence of polar windows is still debated. This uncertainty carries over to the diameter correction, where the Milky Way absorption must be known. The correction of the magnitudes for inclination shows a range of functional forms, from $\log R_{25}$ in the RC2 to $1/R_{25}$ in the work of Sandage and Tammann (1976b). These are very different functions, and it is hard to see how they could describe the same physical phenomenon. The correction of the diameter for inclination is so uncertain that at least two authors believe they have shown the correction is unnecessary, while others apply large corrections to galaxies seen edge-on.

The cluster membership lists and average radial velocities also have unacceptable disagreements. Uncertainty over the membership and velocity of faint galaxies is expected because these galaxies are the most

difficult to observe, but the uncertainty is unacceptable for bright, large galaxies as well. The membership of NGC 4569, 4303, and 4192 in the Virgo cluster has been disputed. In the Ursa Major cluster, six bright galaxies had to be rejected before a bright galaxy with well-accepted membership could be found. In both clusters there is disagreement over the average radial velocity, a disagreement of 400 km/s in Virgo and 640 km/s in Ursa Major.

Despite these difficulties, the calculations show that the lower limit to the distance modulus of the Virgo cluster is 30.7 ± 0.2, giving an upper limit to Hubble's constant of 80 ± 9 km/(s*Mpc) if V = 1100 km/s, or 110 ± 12 km/(s*Mpc) if V = 1500 km/s. The upper limit is less than 33.1 ± 0.3, giving a lower limit to Hubble's constant of 30 ± 4 km/(s*Mpc), and possibly as large as 47 ± 5 km/(s*Mpc), depending upon the choice of Virgo galaxy for comparison. These results agree with calculations by other methods, but make doubtful the value of 55 km/(s*Mpc) favored by some researchers.

After this calculation the method is applied to the Ursa Major cluster. The upper limit to Hubble's constant is 80 ± 8 km/(s*Mpc), and the lower limit is at least 28 ± 3 km/(s*Mpc), and possibly as high as 47 ± 5 km/(s*Mpc), depending upon the Ursa Major galaxy used for comparison. These results are close to the results from

the Virgo cluster, suggesting the Local Group has a component of motion toward Ursa Major as well as toward Virgo. This agrees with the known distribution of mass near the Local Group.

The method is then 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. This comparison shows that there is no discernable absorbing material in the Virgo or Ursa Major clusters, or in the intergalactic space behind them. It also shows that the clusters are exerting significant gravitational force on the groups of galaxies which surround them. This means that the Local Group is not the only group of galaxies with a component of motion toward the clusters. This gravitational influence extends to radial velocities of about 2500 km/s relative to the clusters, giving an extent of $2500/H_0$ Megaparsecs. The figures suggest an upper limit to H_0 of 105 km/(s*Mpc), so the extent of gravitational influence is greater than 24 Mpc.

Calculations of Hubble's constant usually cause bitter debates. To alleviate this situation M31 is compared with the brightest quasar, 3C 273. It has a V magnitude of 12.8, a B-V color of +0.21, and a radial velocity of 47,400 km/s. This gives an upper limit to Hubble's constant of 980 km/(s*Mpc), which even Hubble would have believed.

LITERATURE CITED

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Aaronson, M., Mould, J., and Huchra, J. 1980, Astrophys. J., 237, 655.

Aaronson, M., Mould, J., Huchra, J., Sullivan, W. T., Schommer, R. A., and Bothun, G. D. 1980, Astrophys. J., 239, 12.

Abell, G. O. 1958, Astrophys. J. Suppl., 3, 211.

Arp, H. 1968, Publ. Ast. Soc. Pacific, 80, 129.

Bergh, S. van den 1960, Astrophys. J., 131, 215.

Bergh, S. van den 1967, Astronom. J., 72, 70.

Bergh, S. van den 1977, IAU Colloq. 37, 14.

Bothun, G. D. 1982, Astrophys. J. Suppl., 50, 39.

Bottinelli, L., and Gouguenheim, L. 1976, Astr. Astrophys., 47, 381.

Burbidge, E. M., and Hodge, P. M. 1971, Astrophys. J., 166, 1.

Burbidge, G. 1977, Centre National pour les Recherches Scientifiques, Colloq. 263, 555.

Burstein, D., and Heiles, C. 1978, Astrophys. J., 225, 40.

Burstein, D., and Heiles, C. 1982, Astronom. J., 87, 1165.

Burstein, D., and Heiles, C. 1984, Astrophys. J. Suppl., 54, 33.

Capelato, H., Dominguez-Tenreiro, R., Mazure, A., and Salvador-Sole, E. 1983, Astr. Astrophys., 117, 17.

Chamaraux, P., Balkowski, C., and Gerard, E. 1980, Astr. Astrophys., 83, 38.

Davis, M., and Peebles, P. J. E. 1983, Ann. Rev. Astron. Astrophys., 21, 109.

Davies, R. D., and Lewis, B. M. 1973, Mon. Not. R. Astr. Soc., 165, 231.

Dickel, J. R., and Rood, H. J. 1978, Astrophys. J., 223, 391.

Dressler, A. 1980, Astrophys. J., 236, 351.

Fairall, A. P. 1978, Mon. Not. R. Astr. Soc., 183, 59P.

Fesenko, B. I. 1979, Soviet Astronomy, 23, 144.

Fesenko, B. I. 1980, Soviet Astronomy, 24, 546.

Fisher, J. R., and Tully, R. B. 1981, Astrophys. J. Suppl., 47, 139.

Ftaclas, C., Fanelli, M., Struble, M., and Zuber, M. 1981, Astrophys. J., 245, L5.

Geller, M. J., and Huchra, J. P. 1983, Astrophys. J. Suppl., 52, 61.

Giovanardi, C., Helou, G., Salpeter, E. E., and Krumm, N. 1983, Astrophys. J., 267, 35.

Giovanelli, R., and Haynes, M. P. 1983, Astronom. J., 88, 881.

Godwin, J. G., and Peach, J. V. 1979, Nature, 277, 364.

Gorenstein, M. V., and Smoot, G. F. 1981, Astrophys. J. 244, 361.

Graham, J. A. 1976, Astronom. J., 81, 681.

Gudehus, D. H. 1973, Astronom. J., 78, 583.

Heidmann, J., Heidmann, N., and de Vaucouleurs, G. 1972a, Mem. R. Astr. Soc., 75, 85.

Heidmann, J., Heidmann, N., and de Vaucouleurs, G. 1972b, Mem. R. Astr. Soc., 76, 105.

Heidmann, J., Heidmann, N., and de Vaucouleurs, G. 1972c, Mem. R. Astr. Soc., 76, 121.

Heiles, C. 1976. Astrophys. J., 204, 379.

Helou, G., Salpeter, E. E., and Krumm, N. 1979, Astrophys. J., 228, L1.

Helou, G., Giovanardi, C., Salpeter, E. E., and Krumm, N. 1981, Astrophys. J. Suppl., 46, 267.

Hinks, A. R. 1911, Mon. Not. R. Astr. Soc., 71, 588.

Hodge, P. W. 1981, Ann. Rev. Astron. Astrophys., 19, 357.

Hodge, P. W., and Kennicutt, R. C. 1982, Astronom. J., 87, 264.

Holmberg, E. B. 1946, Medd. Lunds. Obs. Ser. 2, No. 136.

Holmberg, E. B. 1958, Medd. Lunds. Obs. II, 1.

Holmberg, E. B. 1974, Astr. Astrophys., 35, 121.

Hubble, E. 1926, Astrophys. J., 64, 321.

Hubble, E. 1934, Astrophys. J., 79, 8.

Huchra, J., Davis, M., Latham, D., and Tonry, J. 1983, Astrophys. J. Suppl., 52, 39.

Huchra, J. P., and Geller, M. J. 1982, Astrophys. J., 257, 423.

Huchtmeier, W., Tammann, G., and Wendker, H. 1976, Astr. Astrophys., 46, 381.

Jaakkola, T. 1971, Nature, 234, 534.

Jaakkola, T., and Moles, M. 1976, Astr. Astrophys., 53, 389.

Jones, D. H. P. 1973, Astrophys. J. Suppl., 25, 487.

Kennicutt, R. C. 1983, Astronom. J., 88, 483.

Kent, S. M. 1981, Astrophys. J., 245, 805.

Kiang, T. 1968, Dunsink Observ. Publ., Vol. 1, No. 5.

Knapp, G. R., and Kerr, F. J. 1974, Astr. Astrophys., 35, 361.

Kowal, C. T. 1969, Publ. Ast. Soc. Pacific, 81, 608.

Kraan-Korteweg, R. C. 1982, Astr. Astrophys. Suppl., 47, 505.

Krumm, N., and Salpeter, E. E. 1979, Astrophys. J., 228, 64.

Lewis, B. M. 1975, Mem. R. Astr. Soc., 78, 75.

Mayall, N. U. 1934, Publ. Ast. Soc. Pacific, 46, 134.

Mineur, H. 1938, Annales d'Astrophysique, 1, 97.

Moles, M., and Nottale, L. 1981, Astr. Astrophys., 100, 258.

Mould, J., Aaronson, M., and Huchra, J. 1980, Astrophys. J., 238, 458.

McClure, R. D., and Crawford, D. L. 1971, Astronom. J., 76, 31.

McClure, R. D., and Racine, R. 1969, Astronom. J., 74, 1000.

Nilson, P. 1973, Uppsala Obs. Ann. Vol. 6.

Noonan, T. W. 1971, Astronom. J., 76, 190.

Oort, J. H. 1938, Annales d'Astrophysique, 1, 71.

Peterson, B. M. 1970, Astronom. J., 75, 695.

Peterson, B. M., Strom, S. E., and Strom, K. M. 1979, Astronom. J., 84, 735.

Peterson, S. D. 1979, Astrophys. J. Suppl., 40, 527.

Reaves, G. 1983, Astrophys. J. Suppl., 53, 375.

Roberts, M. S. 1975, "Radio Observations of Neutral Hydrogen in Galaxies", in Galaxies and the Universe, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: University of Chicago Press), p. 309.

Rubin, V. C., Thonnard, N., Ford, W., Roberts, M., and Graham, J. A. 1976, Astronom. J., 81, 687.

Sandage, A. 1961, Astrophys. J., 133, 355.

Sandage, A. 1973, Astrophys. J., 183, 711.

Sandage, A. 1976, Astrophys. J., 205, 6.

Sandage, A. 1983, Astronom. J., 88, 1108.

Sandage, A., and Tammann, G. A. 1974a, Astrophys. J., 191, 603.

Sandage, A., and Tammann, G. A. 1974b, Astrophys. J., 194, 559.

Sandage, A., and Tammann, G. A. 1976a, Astrophys. J., 207, L1.

Sandage, A., and Tammann, G. A. 1976b, Astrophys. J., 210, 7.

Sandage, A., and Tammann, G. A. 1981, A Revised Shapley-Ames Catalog of Bright Galaxies (Washington, D.C.: Carnegie Institution of Washington).

Schechter, P. 1976, Astrophys. J., 203, 297.

Schechter, P., and Press, W. H. 1976, Astrophys. J., 203, 557.

Seldner, M., Siebers, B., Groth, E. J., and Peebles, P. J. E. 1977, Astronom. J., 82, 249.

Shane, C. D. 1968, "Distribution of Galaxies", in Galaxies and the Universe, ed. A. Sandage (Chicago: University of Chicago Press).

Shane, C. D., and Wirtanen, C. A. 1967, Publ. Lick Obs., 22, 1.

Stauffer, J. R. 1983, Astrophys. J., 264, 14.

Strom, S. E. 1980, Astrophys. J., 237, 686.

Sturch, C. 1966, Astrophys. J., 143, 774.

Sulentic, J. 1977, Astrophys. J., 211, L59.

Sulentic, J. 1980, Astrophys. J., 241, 67.

Tammann, G. A. 1972, Astr. Astrophys., 21, 355.

Tammann, G. A. 1976, Royal Greenwich Obs. Bul., 182, 154.

Tammann, G. A. 1977, IAU Colloq., 37, 43.

Teerikorpi, P. 1981, Astr. Astrophys., 98, 300.

Tully, R. B. 1972, Mon. Not. R. Astr. Soc., 159, 35P.

Tully, R. B., and Fisher, J. R. 1977, Astr. Astrophys., 54, 661.

Turner, E. L., and Gott, J. R. 1976, Astrophys. J. Suppl., 32, 409.

Vaucouleurs, G. de 1958, Astrophys. J., 128, 465.

Vaucouleurs, G. de 1959, Astrophys. J., 130, 728.

Vaucouleurs, G. de 1961, Astrophys. J. Suppl., 5, 233.

Vaucouleurs, G. de 1975, "Nearby Groups of Galaxies", in Galaxies and the Universe, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: University of Chicago Press), p. 557.

Vaucouleurs, G. de 1978, Astrophys. J., 223, 730.

Vaucouleurs, G. de 1982a, Nature, 229, 303.

Vaucouleurs, G. de 1982b, Astrophys. J., 253, 520.

Vaucouleurs, G. de, and Bollinger, G. 1979, Astrophys. J., 233, 433.

Vaucouleurs, G. de, and Buta, R. 1983, Astronom. J., 88, 939.

Vaucouleurs, G. de, and Malik, G. M. 1969, Mon. Not. R. Astr. Soc., 142, 387.

Vaucouleurs, G. de, and Pence, W. D. 1978, Astronom. J., 83, 1163.

Vaucouleurs, G. de, and Pence, W. D. 1979, Astrophys. J. Suppl., 40, 425.

Vaucouleurs, G. de, and Vaucouleurs, A. de 1963, Astronom. J., 68, 96.

Vaucouleurs, G. de, and Vaucouleurs, A. de 1964, Reference Catalogue of Bright Galaxies (Austin: University of Texas Press).

Vaucouleurs, G. de, and Vaucouleurs, A. de 1972, Nature, 236, 166.

Vaucouleurs, G. de, and Vaucouleurs, A. de 1973, Astr. Astrophys., 28, 109.

Vaucouleurs, G. de, Vaucouleurs, A. de, and Buta, R. 1981, Astronom. J., 86, 1429.

Vaucouleurs, G. de, Vaucouleurs, A. de and Corwin, H. G. 1976, Second Reference Catalogue of Bright Galaxies (Austin: University of Texas Press).

Zwicky, F., Herzog, E., and Wild, P. 1961, Catalogue of Galaxies and of Clusters of Galaxies, Vol. I (Pasadena: California Institute of Technology).

Zwicky, F., and Herzog, E. 1963, Catalogue of Galaxies and of Clusters of Galaxies, Vol. II (Pasadena: California Institute of Technology).

Zwicky, F., Karpowicz, M., and Kowal, C. T. 1965, Catalogue of Galaxies and Clusters of Galaxies, Vol. V (Pasadena: California Institute of Technology).

Zwicky, F., and Herzog, E. 1966, Catalogue of Galaxies and Clusters of Galaxies, Vol. III (Pasadena: California Institute of Technology).

Zwicky, F., and Herzog, E. 1968, Catalogue of Galaxies and Clusters of Galaxies, Vol. IV (Pasadena: California Institute of Technology).

Zwicky, F., and Kowal, C. T. 1968, Catalogue of Galaxies and Clusters of Galaxies, Vol. VI (Pasadena: California Institute of Technology).

APPENDICES

APPENDIX A

INTRODUCTION TO ASTRONOMICAL MAGNITUDES AND PHOTOMETRY

APPENDIX A

Introduction to Astronomical Magnitudes and Photometry

Astronomers use the system of magnitudes to specify the brightness of celestial objects. This system has been inherited from Hipparchus (author of the oldest known star catalog) and the early Greek astronomers, who called the brightest stars first magnitude, the stars noticeably fainter second magnitude, and so on. The faintest stars detectable to the unaided human eye on a very clear night are fifth or sixth magnitude in this system. The magnitude system is in some sense "backward", for the larger the magnitude, the fainter the star.

Fortunately, the response of the human eye is proportional to the logarithm of the brightness of the observed object, so when the magnitude system was recalibrated with light-sensitive instruments the mathematics was easy. Between 1930 and 1955 the magnitude system was redefined, using photocells for detectors instead of an astronomer's eye and brain, because the new photoelectric instruments were much more reliable in measuring the brightness of faint stars.

The study of the brightness of celestial objects is called photometry, from the Greek roots for "light measuring". Whenever photometry of a celestial object is undertaken the photocell and filter combination must be specified so that other observers can reproduce the observations, if necessary. The most common photometric system is the UBV system, which uses a 1P21 photocell with ultraviolet (U), blue (B), and visual(V), that is, yellow, filters. Before the UBV system the most common system was the pg, pv system, which used photographic plates as detectors, one in the blue photographic (pg) passband and one in the yellow photovisual (pv) passband.

Assume that observations are to be made in the UBV system with the V filter. To determine the V magnitude of a star (or galaxy), its image through the V filter is centered on the detector inside the phototube and the output of the tube is measured for a fixed amount of time, usually ten to sixty seconds. This output is proportional to the flux received from the star. To convert the observed flux to a magnitude, a standard star, whose magnitude is known, must also be observed and its flux recorded. Hundreds of standard stars have been defined in all parts of the sky. Let f be the flux from the star to be studied and F the flux from the standard star. Then

$$m_S - m_O = 2.5 \log(f/F)$$

where m_S is the known magnitude of the standard star and

m_o is the magnitude of the star whose magnitude is being observed.

The observed magnitude of a star, called the apparent magnitude, m, depends upon the intrinsic brightness of the star and its distance from the Earth. The flux received from a star decreases as the square of its distance, $f \propto d^2$. To study the distance of a star we define the absolute magnitude, M, to be the apparent magnitude which would be observed if the star were exactly ten parsecs away. A parsec, abbreviated pc, is the distance at which the radius of the Earth's orbit subtends one second of arc. Suppose we have two identical stars, one a standard star 10pc away, the other at some unknown distance, d. Then

$f/F = d^2/10^2$

so

$m - M = 2.5 \log(f/F) = 2.5 \log(d/10)^2 = 5 \log(d/10)$.

The distance modulus, μ, is defined as

$\mu = m - M = 5 \log(d/10)$.

Thus, μ is a measure of the logarithm of the distance to an object.

Distances to galaxies are typically several hundred thousand to a few million parsecs. To streamline the notation, distances to galaxies are usually given in megaparsecs, abbreviated Mpc, where 1 Mpc = 10^6 pc.

The magnitude may be measured with the U, B, or V filter. It is customary to specify the V magnitude. The U and B observations are expressed in magnitude differences, called color indices or colors. The standard colors are B-V and U-B, where the symbols mean B magnitude minus V magnitude, and U magnitude minus B magnitude. The colors are a measure of the temperature of the object; the hotter the object, the smaller the value of the color. Objects with low values of B-V and U-B are hot and blue, while those with high values are cool and red. This is complicated by the effect interstellar matter has on starlight. The matter preferentially scatters the blue light, but allows the red light to pass. Thus, the observed light is said to be reddened. If the intrinsic color of the star is known, then the color excess of the object is defined as

$$(B-V)_{observed} - (B-V)_{intrinsic} = E(B-V)$$

where E(B-V) is the color excess.

The interstellar matter also absorbs starlight, decreasing its intensity as well as making it appear redder. The absorption in the V magnitude is called the visual absorption, A_V, and

$$m_V - M_V = 5 \log(d/10) + A_V.$$

Because the same matter does the absorbing and the reddening we expect a simple relation between A_V and E(B-V). The ratio of these values is called the ratio of

total to selective absorption, R,

$R = A_V/E(B-V)$.

Observations show that R is very nearly equal to 3.0.

Oftentimes, in studying galaxies, the blue magnitude m_B is the most important, so the blue absorption, A_B, becomes important. Because

$m_B = V + (B-V)$,

it is found

$A_B/E(B-V) = \{A_V + E(B-V)\}/E(B-V) = R + 1$.

APPENDIX B

SUPPLEMENTARY TABLES

APPENDIX B

SUPPLEMENTARY TABLES

Table 23. Corrected RC2 system diameters of Local Group galaxies.

	Source of the Milky Way correction	
Galaxy	RC2	B+H *
M31	3.19 ± 0.03	3.18 ± 0.03
M33	2.77 ± 0.03	2.76 ± 0.03

* Burstein and Heiles (1984)

Table 24. Holmberg system diameters of Local Group galaxies with corrections in the HHV system.

	Source of the raw diameter	
Galaxy	Holmberg	de Vaucouleurs
M31	2.27 ± 0.07	2.32 ± 0.07
M33	1.89 ± 0.06	1.82 ± 0.06

Table 25. Corrected RC2 system magnitudes of Local Group galaxies.

	Source of the Milky Way correction	
Galaxy	RC2	B+H *
M31	3.59 ± 0.11	3.68 ± 0.11
M33	5.79 ± 0.07	5.92 ± 0.07

* Burstein and Heiles (1984)

Table 26. Corrected magnitudes in the B system of the RSA for Local Group galaxies.

Galaxy	listed in RSA	calculated from RSA formula
M31	2.71 ± 0.42	3.31 ± 0.32
M33	5.69 ± 0.11	5.69 ± 0.11

Table 27. Holmberg system magnitudes of Local Group galaxies with three different correction schemes.

	Correction Scheme		
Galaxy	Holmberg	HHV	S+T *
M31	3.29 ± 0.12	3.34 ± 0.12	3.63 ± 0.12
M33	5.82 ± 0.09	5.87 ± 0.09	5.69 ± 0.09

* Sandage and Tammann (1976b)

Table 28. Logarithms of corrected RC2 system diameters of the largest Virgo cluster galaxies.

	Source of the Milky Way correction		
Galaxy	RC2	RSA *	B+H +
NGC 4569	1.93 ± 0.03	1.91 ± 0.03	1.92 ± 0.03
NGC 4517	1.85 ± 0.05	1.84 ± 0.05	1.84 ± 0.05
NGC 4192	1.89 ± 0.04	1.87 ± 0.04	1.88 ± 0.04
NGC 4321	1.85 ± 0.03	1.83 ± 0.03	1.83 ± 0.03

* In the RSA $A_B = 0$ for Virgo galaxies
\+ Burstein and Heiles (1984)

Table 29. Logarithms of Holmberg system diameters of the largest Virgo cluster galaxies with HHV corrections.

Galaxy	log a
NGC 4569	1.024 ± 0.046
NGC 4517	1.026 ± 0.049
NGC 4192	0.982 ± 0.050
NGC 4321	0.994 ± 0.045

Table 30. Corrected magnitudes in the B system of the RC2 for the brightest Virgo cluster galaxies.

	Source of the Milky Way correction		
Galaxy	RC2	RSA *	B+H +
NCG 4569	9.78 ± 0.11	9.97 ± 0.11	9.89 ± 0.11
NCG 4321	9.86 ± 0.08	10.05 ± 0.08	10.01 ± 0.08
NCG 4303	9.97 ± 0.08	10.17 ± 0.08	10.16 ± 0.08

* In the RSA $A_B = 0$ for Virgo galaxies.
+ Burstein and Heiles (1984)

Table 31. Corrected magnitudes in the B system of the RSA for the brightest Virgo cluster galaxies.

Galaxy	corrected magnitude
NGC 4569	9.39 ± 0.22
NGC 4321	9.79 ± 0.11
NGC 4303	9.85 ± 0.11

Table 32. Holmberg system magnitudes of the brightest Virgo cluster galaxies with three different correction schemes.

	Correction Scheme		
Galaxy	Holmberg	HHV	S+T *
NGC 4569	9.60 ± 0.13	9.79 ± 0.13	9.66 ± 0.13
NGC 4321	10.01 ± 0.07	10.06 ± 0.07	10.04 ± 0.07
NGC 4303	9.82 ± 0.06	9.96 ± 0.06	9.98 ± 0.06

* Sandage and Tammann (1976b)

Table 33. Logarithms of corrected RC2 system diameters of the smallest Virgo cluster galaxies.

	Source of the Milky Way correction	
Galaxy	RC2	RSA
NGC 4299	1.25 ± 0.04	1.23 ± 0.04
NGC 4234	1.12 ± 0.04	1.10 ± 0.04
NGC 4630	1.21 ± 0.04	1.20 ± 0.04
NGC 4633	1.25 ± 0.04	1.24 ± 0.04
IC 3258	1.21 ± 0.05	1.20 ± 0.05
IC 3521	1.06 ± 0.05	1.04 ± 0.05
IC 3665	1.01 ± 0.05	1.00 ± 0.05
IC 3073	1.03 ± 0.05	1.01 ± 0.05

Table 34. Corrected magnitudes in the B system of the RC2 for the faintest Virgo cluster galaxies.

	Source of the Milky Way correction	
Galaxy	RC2	RSA
NGC 4299	12.56 ± 0.12	12.84 ± 0.12
NGC 4234	13.15 ± 0.10	13.35 ± 0.10
NGC 4630	12.84 ± 0.20	13.04 ± 0.20
NGC 4633	13.33 ± 0.11	13.52 ± 0.11
IC 3258	13.52 ± 0.14	13.71 ± 0.14
IC 3521	13.69 ± 0.13	13.88 ± 0.13
IC 3665	14.53 ± 0.20	14.72 ± 0.20
IC 3073	14.68 ± 0.20	14.87 ± 0.20

Table 35. Lower limits to the distance modulus of the largest and brightest Virgo cluster galaxies in the RC2 system with A = 0, as in the RSA.

	Comparison	
Galaxy	Diameters	Magnitudes
NGC 4569	30.49 ± 0.25	30.48 ± 0.19
NGC 4321	30.88 ± 0.24	30.56 ± 0.18
NGC 4303	---	30.68 ± 0.18
NGC 4517	30.83 ± 0.33	---
NGC 4192	30.69 ± 0.28	---

Table 36. Lower limits to the distance modulus of the largest and brightest Virgo cluster galaxies in the RC2 system with Milky Way corrections from Burstein and Heiles (1984).

	Comparison	
Galaxy	Diameters	Magnitudes
NGC 4569	30.40 ± 0.25	30.31 ± 0.19
NGC 4321	30.82 ± 0.24	30.43 ± 0.18
NGC 4303	---	30.58 ± 0.18
NGC 4517	30.76 ± 0.33	---
NGC 4192	30.57 ± 0.28	---

Table 37. Upper limits to the distance modulus of the smallest, faintest Virgo cluster galaxies in the RC2 system with A = 0, as in the RSA.

	Comparison	
Galaxy	Diameters	Magnitudes
NGC 4299	31.87 ± 0.23	31.25 ± 0.16
NGC 4234	32.51 ± 0.25	31.76 ± 0.14
NGC 4630	32.04 ± 0.23	31.45 ± 0.22
NGC 4633	31.85 ± 0.25	31.93 ± 0.15
IC 3258	32.04 ± 0.29	32.12 ± 0.17
IC 3521	32.83 ± 0.29	32.39 ± 0.16
IC 3665	33.05 ± 0.29	33.13 ± 0.23
IC 3073	32.99 ± 0.29	33.28 ± 0.23

Table 38. Lower limits to the distance modulus of the brightest Virgo cluster galaxies in the B system of the RSA.

	Assumed M31 distance modulus	
Galaxy	3.13	2.71
NGC 4569	30.36 ± 0.37	30.78 ± 0.37
NGC 4321	30.76 ± 0.31	31.18 ± 0.31
NGC 4303	30.83 ± 0.31	31.25 ± 0.31

Table 39. Lower limits to the distance modulus of the brightest Virgo cluster galaxies in the Holmberg magnitude systyem.

	Corrections		
Galaxy	Holmberg	HHV	S+T *
NGC 4569	30.41 ± 0.21	30.55 ± 0.21	30.13 ± 0.21
NGC 4321	30.82 ± 0.18	30.82 ± 0.18	30.51 ± 0.18
NGC 4303	30.63 ± 0.18	30 72 ± 0.18	30.45 ± 0.18

* Sandage and Tammann (1976b)

Table 40. Lower limits to the distance modulus of the largest Virgo cluster galaxies in the Holmberg diameter system.

	Source of the diameter of M31	
Galaxy	Holmberg	de Vaucouleurs
NGC 4569	30.35 ± 0.51	30.61 ± 0.50
NGC 4321	30.50 ± 0.48	30.76 ± 0.48
NGC 4517	30.34 ± 0.50	30.60 ± 0.50
NGC 4192	30.56 ± 0.52	30.82 ± 0.50

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