THE ASTROPHYSICAL JOURNAL, 303:1–9, 1986 April 1

THE DISTANCE SCALE: PRESENT STATUS AND FUTURE PROSPECTS[1]

MARC AARONSON
Steward Observatory, University of Arizona

AND

JEREMY MOULD
Palomar Observatory, California Institute of Technology
Received 1985 September 27; accepted 1985 September 30

ABSTRACT

The Hubble constant is arguably the single most important quantity in observational cosmology. Unfortunately, after more than half a century of intensive study, the value of H_0 obtained via calibration of the extragalactic distance scale remains a source of tremendous controversy. Solution of the problem requires a global indicator which should ideally have the following attributes: (1) sound physical basis; (2) quantitative (and not subjective) observables; (3) measurables needing minimal corrections; (4) applicability over a wide distance range; and (5) small scatter.

The leading contender for such an indicator appears to be the relation between galaxian infrared luminosity and rotation speed as measured by the velocity width of the 21 cm profile. Results obtained to date from exploitation of the IR/H I relation are summarized. These include (1) detailed mapping of the velocity field in the Local Supercluster, leading to Virgocentric motion of ~ 300 km s^{-1} and (2) the detection of bulk Supercluster movement of a comparable size toward Hydra-Centaurus, which fully accounts for the dipole anisotropy in the microwave background.

Correction for all velocity deviation leads to a high value ($H_0 \approx 90$ km s^{-1} Mpc^{-1}) for the expansion rate. The principal uncertainty in this result (or any other current estimate for the Hubble constant) remains calibration of the local distance scale. In this regard, it is anticipated that the Hubble Space Telescope can make a substantial contribution. In particular, it is argued that the thrust of the attack with HST should be to measure Cepheid distances to a number of nearby galaxies which can in turn serve as calibrators for the IR/H I method.

Subject headings: cosmology — galaxies: distances

I. INTRODUCTION

Among the various cosmological parameters (H_0, q_0, Ω_0, T_0, Λ), the expansion rate is, in principle, the most straightforward to determine. The prescription is, in fact, trivial: measure a velocity, measure a distance, and divide. Yet even with 50 years of heroic attack using the world's premier optical telescopes, the problem is widely regarded today as unsolved. This is surely a reflection of the vastness of astronomical distances, coupled with the rubbery nature of the many available yardsticks, whose application invariably requires some degree of personal judgment.

The importance of the Hubble constant hardly needs recapitulation since it enters into a large fraction of extragalactic calculations. In addition to delineating the size of the universe, H_0 also allows an estimate of its age. The amount of agreement between this time and the other chronometers continues to hold considerable interest since it provides our best constraint on the zero-point pressure term Λ. A question that has become closely associated with the distance scale involves deviations from uniform Hubble flow. For instance, it is now virtually universally recognized that the Virgo mass concentration exerts a nontrivial gravitational influence on motion of the Local Group. The amount of this perturbation in turn leads to a direct estimate of the mass density parameter Ω_0. Additional motivation in this area is provided by observations of the dipole anisotropy in the microwave background since identification of the accelerator(s) involved has important implications with regard to the large-scale mass distribution in the universe.

Most current estimates place H_0 in the range 40–110 km s^{-1} Mpc^{-1}. As is widely known, the distribution of values within these limits is decidedly non-Gaussian, reflecting the influence of the chief protagonists in the field: A. Sandage and G. Tammann, on the one hand, and G. de Vaucouleurs, on the other. It would be hopeless in a paper of this brevity to do any sort of justice to their work, or the work of numerous other contributors (for recent independent reviews the reader is referred to Hodge 1981, Davis and Peebles 1983, and Rowan-Robinson 1985).

Rather, our goals in this article are threefold. First, we give a critical review of the merits of some popular distance indicators (§ II). We conclude from this discussion that the infrared magnitude/H I relation is the most promising of the secondary indicators for mapping the far-flung Hubble flow, and summarize (§ III) the current status of results from application of this method. Finally, we consider (§ IV) the prospect of measuring a reliable expansion rate with the Hubble Space Telescope (HST).

II. WHAT MAKES A GOOD DISTANCE INDICATOR?

The traditional approach to the problem of constructing the extragalactic distance scale involves three basic steps. First, so-called primary indicators (e.g., Cepheids, RR Lyrae vari-

[1] Pierce Prize Lecture, 165th Meeting of the American Astronomical Society.

ables, etc.) are calibrated within the Milky Way. Next, the zero points of various secondary methods (H II region sizes, supergiants, etc.) are determined from nearby galaxies whose distances come from primary means. Finally, the secondary techniques are applied to more distant systems.

While there seems to be no shortage of indicators available (27 alone are listed in Table 5 of Hodge 1981), considerable flexibility exists in how best to pick and choose one's way through them. In this regard, the "spread the risk" view of de Vaucouleurs philosophically differs from what has tended to be an "all eggs in one (or maybe two) basket(s)" approach of Sandage and Tammann.

Beyond fundamental trigonometric parallax, all distance methods used by astronomers require some leap of faith. It would clearly be helpful, though, to have a way of ranking the various techniques in some manner that might reflect their reliability. With this aim in mind, we list below five qualities that may provide one such screening process.

Physical basis.—A well-defined underlying connection with physics is certainly a desirable quality. Historically, many of the secondary indicators (e.g., H II region sizes, brightest globular clusters) are based largely on statistical arguments, and lack a precise physical explanation.

Objective measurables.—The characteristics describing a standard candle or ruler should be objectively determined. Again, many of the historical indicators, such as luminosity class, are almost by definition based on subjective estimates. An example of the errors that can creep in appears in Kennicutt's (1979) isophotal work on H II region diameters, indicating systematic problems with older hand-measured values.

Minimal corrections.—Observed quantities are often far removed from those used to calculate moduli. For example, to obtain total galaxy magnitudes in the blue, a typical procedure is to extrapolate concentric aperture photometry using a standard galaxy growth curve, and then to correct for galactic extinction, inclination effect, and redshift. In the case of inclination, the corrections are both large and ill-defined, while extinction at the poles continues to be debated, with this source alone resulting in a 0.2 mag zero-point shift between the de Vaucouleurs and Sandage-Tammann scales. Methods that circumvent such problems are obviously advantageous.

Wide distance range.—Ideally, a secondary indicator should be calibrated via Cepheids but should be employable out beyond any possible flow deviation (i.e., at redshifts greater than 5000 km s^{-1}). Until recently, the general lack of such methods has led to the development of tertiary or even quaternary techniques. For instance, in the classical Sandage-Tammann approach, H II regions (themselves not practical much beyond Virgo) are used to calibrate the bright end of the absolute magnitude–luminosity class relation to overcome problems with the presence of only one nearby Sc I system—M101.

Small scatter.—This is an obvious requirement, but with subtle implications regarding the magnitude-limited nature of most samples. For instance, the familiar Malmquist effect introduces a bias related to the square of the scatter, becoming substantial for $\sigma > 0.5$ mag. Methods involving supernovae and supergiants may circumvent this problem to some extent, but unfortunately, as discussed below, the true scatter in these techniques remains unclear.

Our own judgment of how some well-known indicators stack up against the above criteria is given in Table 1. In the first two rows we consider the principal methods employed in the original Sandage-Tammann program. It is perhaps ironic that Kennicutt's (1979) attempts to put H II region diameters on a more solid footing through isophotal measures led instead to an undermining of the entire approach because they revealed inherent ambiguities in how to calibrate the diameter relation, a point discussed extensively by Mould, Aaronson, and Huchra (1980). After some earlier vacillation, Sandage and Tamman (1985) still hold out promise for luminosity classes, arguing that the $\sigma = 0.88$ mag spread in Virgo Sc I systems drops to $\sigma = 0.38$ mag if one object that is apparently an Sc I-II is eliminated from the sample.

The remaining five entries in column (1), are, in our opinion (along with RR Lyraes and novae), the most promising now available for obtaining the Hubble constant, and we shall comment on each in turn.

a) Cepheids

Cepheid variables are widely regarded as the best of the primary indicators. Their basic physics, involving double ionization zones, is well understood (e.g., Cox 1985), although disagreements between pulsational, evolutionary, and so-called beat and bump masses perhaps remains problematic (Schmidt 1984). The outstanding concerns in the practical application of Cepheids are the calibration of the period-luminosity (P-L) zero point, the abundance dependence of the relation, the internal absorption in other galaxies, and the effects of multiple strip crossings and stochastic mass-loss processes. (We forego discussion of the period-luminosity-color relation since its use is probably impractical with HST). A tractable solution to extinction has been given recently by Freedman (1985), whose multicolor *BVRI* observations of M33 Cepheids yield convincing evidence for a mean internal absorption of $A_V \sim 0.5$ mag. Curiously, while this effect has long been acknowledged for supernovae, considerable debate had arisen over whether it occurs in either Cepheids or super-

TABLE 1

COMPARISON OF DISTANCE INDICATORS

Method	Physical Basis	Quantitative Measures	Minimal Corrections	Wide Distance Range	Small Scatter
H II regions	N	N	Y	N	N
Luminosity class	N	N	Y	N	N
Cepheids	Y	Y	N	N	Y
Blue supergiants	N	Y	N	N	?
Red supergiants	Y?	Y	N	N	?
Supernovae	Y?	Y	Y?	Y	?
IR/H I	Y	Y	Y	Y	Y

giants. Another approach to the problem is via near-infrared photometry, the advantages of which have been discussed extensively in the pioneering work of Madore and collaborators. Unfortunately, the limit of the method with conventional chopping photometers reaches barely out to M31, and the future here clearly lies with IR arrays. Abundance effects on the P-L relation have been considered theoretically by Iben and Tuggle (1975), but the problem awaits an empirical approach.

Unfortunately, the zero point of the P-L relation determined from galactic studies is at present in a rather unsatisfactory state, illustrated by the recent discussions of Caldwell (1983), Schmidt (1984), and Balona and Shobbrook (1984). In particular, the discrepancy in cluster distances obtained from main-sequence fitting and the Strömgren luminosity calibration, first pointed out by Schmidt, has been largely confirmed in the work of Balona and Shobbrook. The later authors find $\phi_{\rm PL} = -1.14 \pm 0.11$, a full 0.36 mag different from Caldwell's value of $\phi_{\rm PL} = -1.50 \pm 0.04$ (and the difference persists with $\phi_{\rm PLC}$). Many subtleties are involved in this area, including for instance the proper choice and fitting of the ZAMS, the correct slope of the P-L relation, cluster membership and abundance questions, and so on.

Several new independent studies have tended to favor the notion of a shrunken distance scale implied by the Strömgren results. Among these are Frenk and White's (1982) analysis of cluster dynamics and the new RR Lyrae study of Blanco and Blanco (1985), both of which suggest a galactic center distance of 7 kpc (compared with the IAU value $R_0 \equiv 10$ kpc!); and the shorter LMC modulus obtained from main-sequence fitting by Schommer, Olszewski and Aaronson (1984). (Chiosi and Pigatto 1985 have attempted to explain the latter result away by invoking convective overshoot. This might seem unsatisfactory, since main-sequence diagrams for Magellanic Cloud clusters older than ~ 3 Gyr, where stars have radiative cores, also support the shorter modulus.) The current debate over the galactic scale and the distance to even the closest neighbor galaxy illustrates one of our principal conclusions, namely, that the largest uncertainty in H_0 now rests in the choice of nearby distances required to calibrate good secondary indicators.

b) Supergiants

The use of supergiants as standard candles continues to be pursued by Sandage, and separately by Humphreys. Both workers agree that the dependence of supergiant luminosity on parent galaxy magnitude is steeper for the blue stars than for the red ones. A physical explanation for this difference involves severe mass loss for stars having $M > 50\ M_\odot$, preventing their evolution over to the cooler region of the H-R diagram (e.g., Maeder 1983).

In our opinion, the use of supergiants as secondary indicators is beset with a number of problems. The true intrinsic scatter in the method, which can only be determined by building on the Cepheid scale, remains very unclear, given the small number of systems having reliable Cepheid distances. The reason for the claimed greater constancy of the red stars at V, as compared to K (2.2 μm, where most of the energy comes out) or bolometrically is somewhat obscure. In the LMC, the brightest bolometric red supergiants are in fact not even the same as the brightest visual ones (Elias, Frogel, and Schwering 1986). Furthermore, extinction effects must somehow be accounted for. Because of foreground dwarf contamination, spectroscopic confirmation, multiple epoch observations to identify variables, or both, are required. On the other hand, this variability itself presents some practical problems if these objects are to be pursued with HST. Extensive observations are needed to identify $V_{\rm max}$, and perhaps to separate out those stars having "violent" light curves which Sandage (1984) argues should be discarded.

The checkered history of M101 possibly best illustrates some of these problems. "Despite a serious study." Sandage and Tammann (1974) could find no red supergiant candidates to their search limit of $V = 21$. In a subsequent investigation, Humphreys and Strom (1983) identified the general onset of the red supergiant population as occurring at $V = 20.9$, and listed a number of brighter candidates as well, prompting them to propose a decrease in the M101 modulus based on the notion, accepted at that time, of a constancy in maximum M_V. In a reevaluation of his original plate material, Sandage (1983) also concluded that brighter red supergiants were present, beginning in fact at $V = 20.1$ mag, although the overlap of his candidate list with that of Humphreys and Strom was very small! In addition, Sandage argued that the lack of Cepheid detections limited the modulus of M101 to his older value of 29.2, and proposed instead a steep dependence of maximum red supergiant brightness on parent system magnitude.

Most recently, Humphreys *et al.* (1985) have obtained IR photometry of some M101 candidates, and have confirmed as supergiants stars selected from both the Sandage and Humphreys-Strom studies. Unfortunately, after all this work, the actual identification of the three brightest red stars in M101 still remains unclear since these could not be unambiguously classified by Humphreys *et al.* These stars remain, though, well within the spectroscopic limits of present technology. One interesting result that did emerge from the Humphreys *et al.* work was that at a modulus of 29.2, the magnitudes of the brightests red candidates approach $M_{\rm bol} = -11$, implying a progenitor mass well above the $\sim 50\ M_\odot$ limit noted earlier. Several groups are now pursuing Cepheid searches in M101, which should ultimately help resolve many of the questions raised now about M supergiants.

c) Supernovae

Supernovae continue to hold out potential for the distance scale. There are two approaches to take. One involves application of the Badde-Wesselink method to type II supernovae, where line and continuum placement are more straightforward. The main problem here may be the substantial blackbody deviation of the energy distribution. Detailed atmosphere modeling is required to account for this effect properly, and preliminary results (Wagoner 1984) suggest a correction toward smaller distance moduli.

The alternate tack is the use of Type I supernovae as standard candles. Unfortunately, the general lack of high-quality light curves combined with the need to restrict the sample to early-type galaxies in order to avoid extinction problems has left open the question of just how small the intrinsic scatter in these objects really is. Furthermore, the origin of Type I supernovae is still under debate. Perhaps most distressing, it now appears that a significant fraction of the Type I supernovae are of a peculiar nature with differing luminosity characteristics (Wheeler and Levreault 1985; Uomoto and Kirshner 1985). These peculiar objects have so far been found only in spirals. The similarity of the infrared light curves reported by Elias *et* *al.* (1981) for two supernovae in NGC 1316 is encouraging, but continued investigation is obviously essential.

*d) The IR/*H I *Relation*

A decade ago, Tully and Fisher (1977) proposed the idea of using rotation as a "standard candle" and, furthermore, of measuring the rotation by means of comparatively easy 21 cm observations, rather than through much more difficult optical means. They were able to show that galaxies in the Virgo and Ursa Major clusters exhibited a well-defined relationship between H I velocity width and diameter, and an even better one between line width and luminosity. (Remarkably, in 1922 Oepik used a three-parameter variant of the approach involving rotation, diameter, and luminosity to obtain a distance of 4.5×10^5 pc to M31, a value far closer to modern estimates than Hubble's 1936 distance of 2.1×10^5 pc.)

The simple physical explanation of what has become known as the Tully-Fisher method relates, of course, to the dependence of both luminosity and disk rotational velocity on galaxian mass. Unfortunately, the technique as originally proposed by Tully and Fisher contained a fundamental flaw: observed velocity widths must be adjusted for inclination effect, and the correction becomes large and uncertain for $i < 45°$. On the other hand, the blue magnitudes must also be corrected for inclination because of self-extinction, but here the correction becomes large and uncertain for $i > 45°$.

With the hope of avoiding this difficulty, we turned 7 years ago to the near-infrared. The H band at 1.6 μm seemed an ideal location, since not ony are absorption effects minimal, enabling unambiguous photometry of edge-on systems, but also the stellar energy distribution peaks at this wavelength, which should therefore better reflect the underlying mass. In an initial study (Aaronson, Huchra, and Mould 1979), our expectations were confirmed. The IR/H I diagrams for the same Virgo and Ursa Major galaxies examined by Tully and Fisher were found to have smaller scatter at H, without any correction for internal absorption, than in the blue.

A further result of the pilot work was a new appreciation of the dynamical origin of the Tully-Fisher method. The slope of the relation was found to be near 10, steeper than had been seen in the optical, but reminiscent of the $L \propto V^4$ power law already observed for elliptical galaxies. In fact, we were able to demonstrate that with the virial theorem and some simple assumptions related to the rotation curve, mass distribution profiles, and the constancy of mass-to-light ratio, a fourth power law naturally followed.

We believe the IR/H I technique now stands as the most powerful and reliable of the available secondary indicators. The method appears to fulfill all our previously stipulated criteria (Table 1): The physical basis is solid. The observables are quantitatively measured. Such corrections as galactic extinction, internal absorption, and redshift effect are negligible. The method can be calibrated with Cepheids in nearby galaxies such as M31 and M33, but can be extended out to great distances (the practical limit for cluster work, set by the sensitivity and resolution limits of Arecibo, is Hercules at $V \approx 11{,}000$ km s^{-1}). Figure 1 shows an example of the IR/H I relation for the Pisces cluster at $V_0 \approx 5300$ km s^{-1}

Perhaps most importantly, the scatter in the method has now been established to be small. The rms dispersion found for various samples is summarized in Table 2. The typical scatter for both clusters and nearby calibrating objects is $\sigma \sim 0.4$. After correcting for infall, 265 galaxies in the Local Supercluster yield $\sigma \sim 0.5$, but this result makes no allowance for peculiar galaxy motions. We adopt $\sigma = 0.45$ mag as a reasonable estimate. Since an amount $\gtrsim 0.25$ mag must be contributed by the observational uncertainties in line width, inclination, H band photometry, and isophotal diameter (see below), the true intrinsic scatter is probably $\sigma \lesssim 0.35$ mag.

To be fair, a number of concerns about the IR/H I method exist, and we turn now to a discussion of these. The most serious potential problem arises from the question of morphological type dependence. The sample of ~ 50 spirals with optical rotation curves obtained by Rubin and collaborators

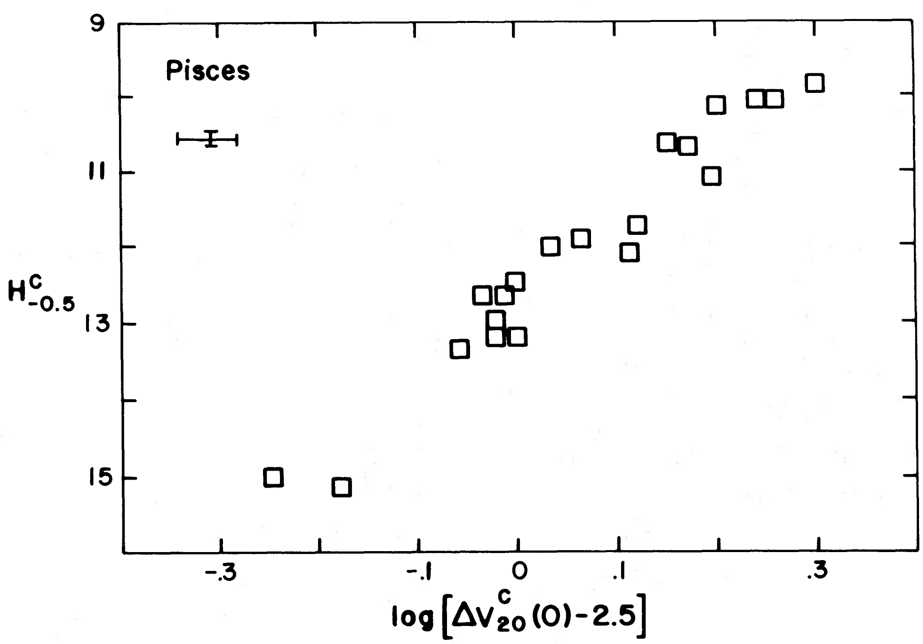

FIG. 1.—The IR/H I relation for galaxies in the Pisces cluster (mean $V_0 \approx 5300$ km s^{-1})

TABLE 2

SCATTER IN THE IR/H I METHOD[a]

Sample	N	σ	Source
Sandage-Tammann calibrators	16	0.42	1
de Vaucouleurs calibrators	13	0.36	1
Virgo Cluster	16	0.45	1
Ursa Major Cluster	24	0.40	1
Local Supercluster	265	0.52	1
Mean of seven distant clusters[b]	91	0.41	2

[a] A linear relation is assumed with slope 10.

[b] Sample contains Pisces, A400, A539, A1367, Coma, Hercules, and A2634/66. Quoted dispersion is the mean for these systems, weighted by galaxy number per cluster. Not included are Cancer and Z74-23, which Aaronson *et al.* 1986 show to be unbound collections of groups, and Pegasus, which appears to be contaminated by members of the background Pisces-Perseus Supercluster.

SOURCES.—(1) Aaronson and Mould 1983. (2) Aaronson *et al.* 1986.

shows a strong segregation with type in their version of the blue Tully-Fisher diagram, which diminishes but is not eliminated when infrared magnitudes are employed (see Whitmore 1984). On the other hand, as shown in Figure 2, our Local Supercluster sample which is 4 times larger contains no evidence for any such effect. A fully satisfactory explanation of these discrepant results has not yet been given. It must partially involve the much higher fraction of Sa galaxies found in the Rubin work than in our own, arising because our galaxies are H I selected, while those in the Rubin studies are simply chosen by size to fit on the spectroscope slit. There is, however, other evidence to suggest that the Rubin sample is unusual, related to the much steeper slope in the blue Tully-Fisher diagram found using their data than has been found in all other optical studies that have been made.

A second concern involves the reality of the fourth-power dependence, both from an observational and theoretical standpoint. The simple assumptions we used in deriving a slope 10 relation seem difficult to reconcile with the presence of dark halos; they have also been questioned on independent grounds by Burstein (1982). These points, while largely irrelevant to the strictly empirical derivation of distances, may be nonetheless connected to the nonlinearity in the IR/H I relation that appears to exist (e.g., Fig. 2 of Aaronson *et al.* 1982*b*). As discussed by Aaronson *et al.* (1986), curvature in the relation seems only partly accounted for by the fractional increase in turbulent velocity with decreasing mass. To allow for such curvature, we have adopted in our latest work a quadratic form of the relation, although the linear version is generally suitable if the galaxies evenly populate the IR/H I plane. We stress, though, that the uncertainty in absolute distance introduced by imprecise knowledge of the slope (and second-order term) is small, i.e., $\lesssim 0.1$ mag.

A third problem involves the use of blue isophotal diameters. The lack of panoramic detectors prevents a zero-pont calibration based on total IR magnitude. To overcome this, we chose early on to refer the *H* band photometry to a fiducial corresponding roughly to one-third the Palomar Sky Survey

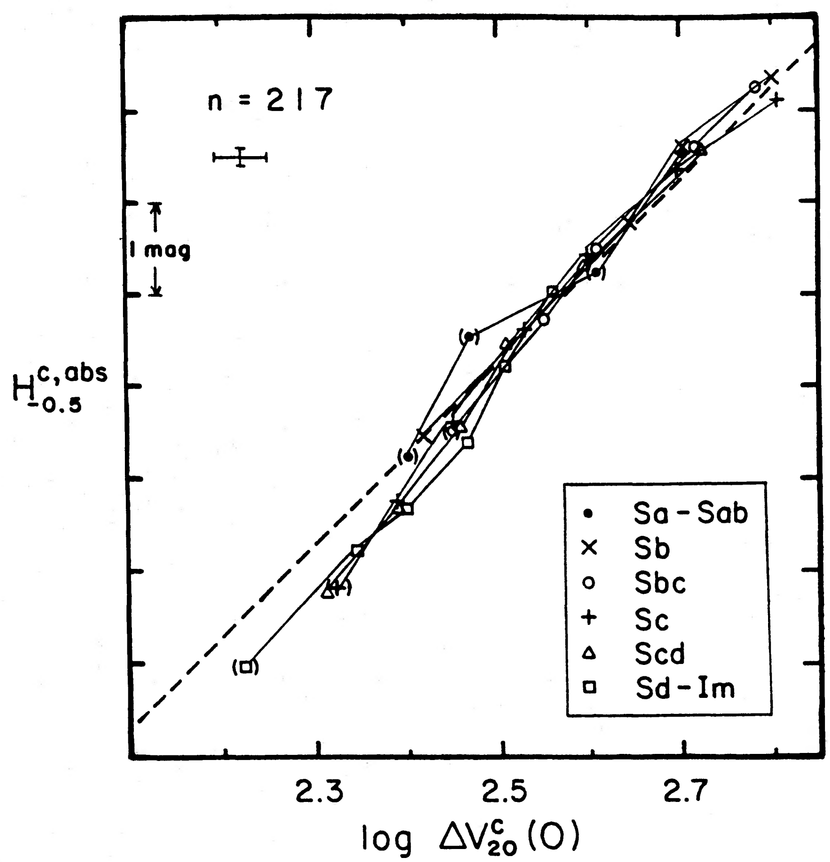

FIG. 2.—Collection of objects in the Local Supercluster binned by morphological type. No evidence of segregation by morphology is visible in this sample.

diameter. However, the accuracy of blue diameters subsequently used in our distant cluster work was called into question by the study of van den Bergh (1981), who pointed out curious differences in the cluster surface brightness properties. These various issues have now been investigated extensively (Aaronson *et al.* 1986) by means of accurate isophotal CCD diameters obtained by Cornell *et al.* (1984) for several hundred distant cluster spirals. This effort has indeed led to the discovery of small systematic errors in the old diameters, although diameters for larger galaxies within the Local Supercluster generally seem to be secure.

Finally, we note that possible environmental factors connected with the IR/H I method continue to elude detection (e.g., Bothun *et al.* 1984, Aaronson *et al.* 1986) and are therefore likely to be unimportant.

III. A DISTANCE SCALE FROM THE IR/H I RELATION

Our construction of a distance edifice had somewhat humble beginnings with the No. 3 0.4 m (16 inch) Kitt Peak telescope and a specially commissioned 0.08 m telescope (Aaronson, Mould, and Huchra 1980). These instruments were employed for very large (up to 1500″) aperture photometry of close galaxies. We found good agreement in relative moduli with the nearby scale of Sandage and Tammann. However, it was (and still remains) impossible to distinguish between their absolute scale and the nearby one of de Vaucouleurs because the relative distances of the available calibrators agree well in both instances.

Our next step was a study of the Virgo cluster distance, leading to a proposed modulus of 31.0 and a Hubble ratio for Virgo of 65 km s^{-1} Mpc^{-1} (Mould, Aaronson, and Huchra 1980). This modulus was 0.7 mag less than the Sandage-Tammann value, even though the zero point was based on their scale. A detailed investigation indicated, however, that Kennicutt's (1979) new isophotal H II region sizes implied a reduction in the Sandage-Tammann ladder at Virgo of more or less the same 0.7 mag.

A first attempt to extend the method beyond the Local Supercluster was made by Aaronson *et al.* (1980), for which the Arecibo facility became of paramount importance. By concentrating on clusters whose member galaxies are generally all at the same distance, the familiar problem of Malmquist bias could be avoided. As it turned out, all four distant groupings studied yielded Hubble ratios substantially higher than the value for Virgo, suggesting a Local Group motion in that direction of $\sim$480 km s^{-1}. This amount was in close accord with the velocity vector implied by the measurements then available of the 3 K anisotropy, and it seemed natural (although, as it turned out, it was premature) to identify the latter as arising from motion entirely within the Local Supercluster. It should be mentioned that the importance of the Supercluster mass concentration with regard to Hubble flow deviations had long been championed by de Vaucouleurs.

If the above conclusion was on the right track, then the implied distortion within the Local Supercluster itself ought to be detected easily. As a result of very generous KPNO and CTIO time allocation, and rather good fortune with the weather, we were able to accumulate in only a few years H band photometry of over 300 Local Supercluster galaxies (Aaronson *et al.* 1982*b*) for which H I profiles had just become available (primarily given in the massive catalog of Fisher and Tully 1981). This allowed us to make (Aaronson and Mould 1983) a careful investigation of the type dependence and scatter in the IR/H I method. More importantly, the data permitted a detailed mapping of the velocity field within the Local Supercluster, allowing measure of both the infall velocity at the distance of the Local Group from Virgo and the random component in Local Group motion (Aaronson *et al.* 1982*a*).

The analysis confirmed the presence of infall, although at a reduced magnitude of 250 ± 64 km s^{-1}. However, a significant peculiar motion of the Local Group was identified, so that the total Virgo-directed motion and total space motion through the Local Supercluster were $\sim$300 and 350 km s^{-1}, respectively. The cosmological density parameter implied by infall alone was small; i.e., $\Omega \approx 0.1$. The zero curvature model of the inflationary scenario currently in vogue can be reconciled with this result only by requiring that 90% of the mass in the universe is dark and unclumped with the visible matter, or the presence of a nonzero cosmological constant (or a combination of both).

Meanwhile, continuing work by the Princeton and Berkeley groups on the dipole anisotropy has led to results that are now in excellent agreement, but which yield a vector of $\sim$600 km s^{-1} that points in a direction some 45° from Virgo. Hence, in view of the velocity field analysis, accounting for the dipole effect solely through motion within the Supercluster no longer seems tenable.

Recently, we completed a multiyear study of the IR/H I relation in 10 adjacent galaxy clusters (Aaronson *et al.* 1986) whose velocities range from Pegasus at $V \approx 4000$ km s^{-1} up to Hercules at $V \approx 11{,}000$ km s^{-1}. The resulting observed Hubble ratios show considerable scatter, arising from the presence of an unaccounted for Local Group motion, the solution for which gives a vector of $\sim 780 \pm 190$ km s^{-1} in a direction only $15 \pm 15°$ from the 3 K anisotropy. We have now concluded that the motion giving rise to the dipole effect can be explained by the vector sum of two principal components. These are Local Group motion within the Supercluster and bulk Supercluster motion as a whole, both velocities being of order 300 km s^{-1}. It is very intriguing that the bulk motion points toward our next nearest neighbor supercluster, Hydra-Centaurus, which may actually be connected to the Local Supercluster by a filamentary chain (Hopp and Materne 1985).

The 10 cluster sample also allows an independent estimate of Virgocentric motion. The result, $\Delta V \approx 300$ km s^{-1}, is in very good agreement with the velocity field study. As discussed in Aaronson *et al.* (1986), the decrease of $\sim$180 km s^{-1} from the results obtained in the earlier cluster effort can be attributed to three main factors—a data set 4 times larger with higher quality line widths, a 50 km s^{-1} revision in the Virgo cluster redshift, and the identification of the diameter errors mentioned earlier. In Figure 3 we show the velocity-distance relation for the full 11 cluster sample (including Virgo), after correction for appropriate Local Group motion. These results appear to leave little room for relative Supercluster motions larger than $\sim$500 km s^{-1}.

What about the Hubble constant? Unfortunately, it remains a sad fact that any attempt to derive H_0 is completely frustrated by the morass of conflicting nearby galaxy distances. M33 provides a simple case in point, as one need only to compare Sandage and Carlson's (1983) modulus of 25.35 mag with Freedman's (1985) modulus of 24.1 mag, both of whose results are ostensibly based on Cepheids!

This is not the place to explain the reasons for such a gross difference. In brief, we believe modern multicolor CCD observations of Cepheids reduced with point-spread function fitting

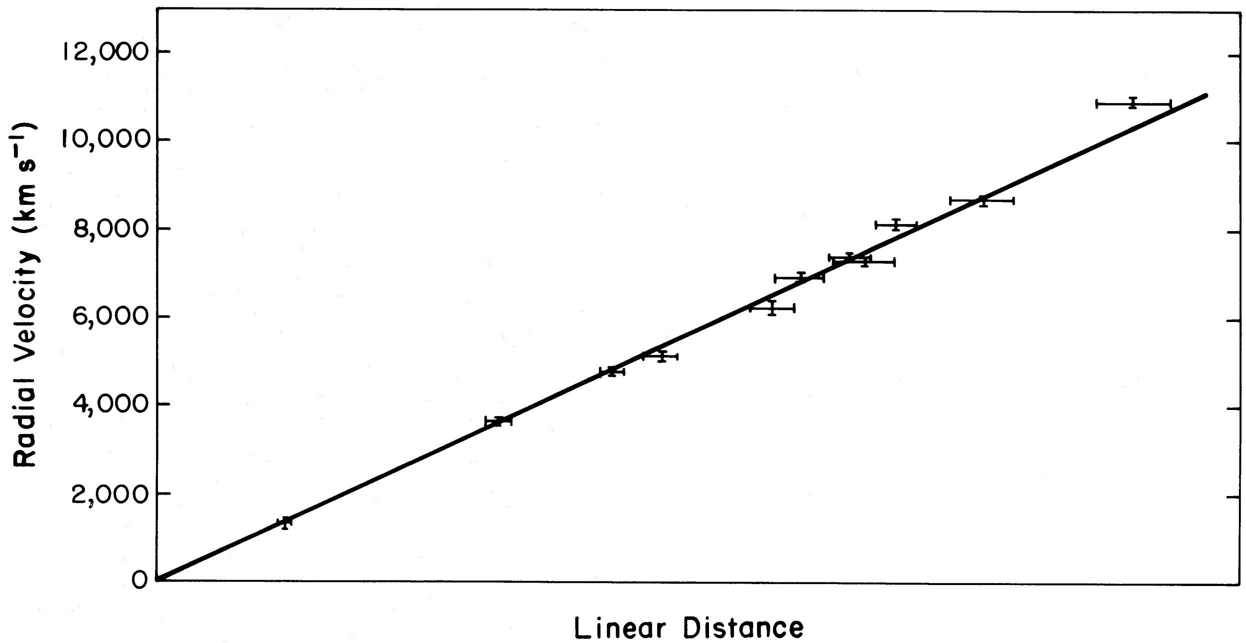

FIG. 3.—The IR/H I diagram for 11 galaxy clusters. The velocity of Virgo, the closest system, has been adjusted for Local Group motion with the Supercluster. The velocities of the remaining clusters have been corrected for motion toward the 3 K dipole anisotropy.

techniques can yield reliable internal reddening estimates and distances. A very preliminary calibration of the IR/H I relation based on such results and companion near-infrared data leads us to offer a best guess value of $H_0 = 90$ km s^{-1} Mpc^{-1} (Aaronson *et al.* 1986). We wish to stress that recent claims of substantially different expansion rates obtained from the Tully-Fisher method or of systematic differences between blue and *H* band results are, for the most part, simply a reflection of the different calibration precepts.

A high value for the Hubble constant is not at present incompatible with the rather wide age range allowed by nucleocosmochronology (e.g., Thielemann and Truran 1985), although globular cluster ages remain problematic. It is interesting, though, that while time scale arguments have often been raised against a high H_0, even the lower values favored by some run into problems with the zero-curvature requirements of the inflationary universe. For example, $T_0 = 13$ Gyr for $H_0 = 50$ km s^{-1} Mpc^{-1}, $\Omega = 1$, and $\Lambda = 0$, in contrast to $T_0 = 18$ Gyr implied by the globular ages (e.g., Sandage and Tammann 1985).

IV. THE PROMISE OF THE HUBBLE SPACE TELESCOPE

The current debate over the distance scale at least partly arises from lack of instrumental tools sufficiently powerful to attack the problem. The imminent launch of the HST will provide, we believe, a magnificent opportunity for pinning down the expansion rate. The intrinsic advantages of the Tully-Fisher method, combined with the results already proven, make a virtually compelling case for orienting the thrust of the attack toward calibration of the IR/H I zero point. Once accomplished, a value for H_0 follows immediately from Figure 3 here (where the formal scatter in Hubble ratio is ± 1 km s^{-1}).

Cepheids remain the indicator of choice for determining the zero point. A large number of potential calibrators are available which appear to be within the capability of the Hubble Telescope. Twenty seven such candidates, along with existing IR/H I data from Aaronson *et al.* (1982*b*), are listed in Table 3, obtained by selecting NGC objects with types in the range Sab–Sdm, inclinations between 50° and 80°, corrected velocity widths from 200 to 600 km s^{-1}, and galactocentric velocities less than 800 km s^{-1}. A better approach than the last criterion might be to make explicit allowance for the Virgocentric flow model. For example, as noted in Table 3, by choosing objects from Aaronson *et al.* (1982*b*) listed as having relative Virgo distances of 0.8 or less, an additional 12 galaxies could be considered as possible calibrators.

How accurately can we expect the Hubble constant to be determined? Cepheid photometry following the strategy discussed below should yield relative distances good to 0.2 mag conservatively. With a 1 σ IR/H I scatter of 0.45 mag and the limiting calibration error of 0.1 mag discussed in § II, a sample of 16 galaxies gives a zero point unknown to 0.16 mag. The current uncertainty of $\sim$0.3 mag in the Cepheid P-L zero point itself implies a final error of some 16% to H_0. However, the on-going ground-based efforts combined with additional work from space will hopefully at least halve the Cepheid zero-pont error, yielding a Hubble constant good to 10%.

Our estimate assumes Cepheid internal reddening can be accounted for by means of the multicolor data but makes no allowance for abundance dependence in the P-L relation. An empirical calibration of this effect might be obtained either from a ground-based attack on a radially distributed sample of Cepheids in M31 and M33, or from space observations of Cepheids in M101 and at least two of its dwarf companions.

We believe it is essential to provide buttressing of the Cepheid scale by additional checks and balances. These include deep main-sequence fitting to the Magellanic Clouds and other Local Group members, along with measurement of horizontal branch and first grant branch tip locations in the

TABLE 3

POTENTIAL NEAR IR/H I CALIBRATORS[a]

Group[b]	Name	Type	i	$V_0{}^c$ (km s^{-1})	$\Delta V_{20}(0)$ (km s^{-1})
Local	M31	Sb	78°	−57	556
	M33	Scd	54	1	253
Sculptor (G1)	N247	Sd	75	188	230
	N253	Sc	79	255	438
	N7793	Sdm	53	234	245
N24/N45	N24	Sc	80	595	230
M81-N2403(G2)	N2403	Scd	60	262	301
	N3031	Sab	58	104	531
CVn I(G3)	N4258	Sbc	72	522	464
	N4826	Sab	60	395	364
M101(G5)	N5585	Sd	52	466	208
N2841(G6)	N2541	Scd	62	600	242
N1023(G7)	N925	Sd	56	709	270
	N949	Sb	55	774	239
	N1003	Scd	72	794	251
Leo triplet(G9)	N3627	Sb	59	619	439
N3184(G12)	N3198	Sc	70	687	343
	N3319	Scd	60	753	265
Coma I (G13)	N4062	Sc	67	765	334
	N4414	Sc	56	723	509
M51(G5)	N5055	Sbc	55	580	487
N3521	N3521	Sbc	65	630	517
	N1744	Sd	58	562	261
	N2903	Sbc	58	451	471
	N3621	Sd	60	469	333
	N5949	Sbc	65	643	230
	N6689	Sd	74	750	252

[a] This table lists NGC objects having IR/H I data from Aaronson *et al.* 1982*b* with types in the range Sab–Sdm; inclinations between 50° and 80°; corrected velocity widths from 200 to 600 km s^{-1}; and galactocentric redshifts less than 800 km s^{-1}. By adopting a Virgocentric flow model and objects having relative Virgo distances $d/d_V \leqslant 0.8$ listed in Aaronson *et al* 1982*b* instead, additional galaxies which might be considered as possible calibrators include N1055, N1249, N1494, N1744, N2090, N2427, N7320, N7331, I1954, U7699, U11707, and A0419-21.

[b] Group number identification from de Vaucouleurs 1975.

[c] Velocity corrected according to 300 sin l cos b.

Population II halo components of M31, M33, and perhaps the nearest Sculptor objects. Also, determining the location of the horizontal branch position in a group of M31 globulars having varying line strengths should nail down once and for all the dependence of this feature on metal abundance.

The above strategy is blocked out in Figure 4. How costly is it in telescope hours? The dominant component comes from the Cepheid observations and the time needed to determine accurate periods (although a novel procedure proposed by Madore and Freedman 1985 may shorten this time). One possible strategy entails observations at 15 epochs with 2000 s wide-band V exposures over a 60 day cycle to find objects of 10–30 day period. For 15 fields in the same number of galaxies, and additional double-epoch URI exposures, the total comes to ~ 175 hr, to which the complementary programs in Figure 2 add another 30%.

Other routes to H_0 are, of course, available. Novae have not been discussed, although the uncertainties in their production rates probably make them more appropriate for ground-based work (see Cohen 1985 for a recent discussion). Supergiants can be calibrated in the same objects selected for the IR/H I zero point, and should be easily resolvable in the dwarf members of the Virgo cluster. Cepheids to Virgo could also be attempted, although the feasibility of such observations remains open to question. However, the Hubble Telescope is probably not a good platform for checking the velocity field since a large sample of objects is necessary for any sensible testing of a flow model. The problem is more appropriate from the ground, where we think it has already largely been solved.

The distance scale path has been a long and tortuous one, but with the imminent launch of the HST there seems good reason to believe that the end is finally in sight.

It is a pleasure to acknowledge our principal collaborators: Greg Bothun, John Huchra, Paul Schechter, Bob Schommer, and Mark Cornell. M. A. also thanks the Smithsonian Astrophysical Observatory, where the written version of this talk was prepared, for a Summer Fellowship. Work reported here was partially supported through NSF grants AST 83-06139 and 83-16629.

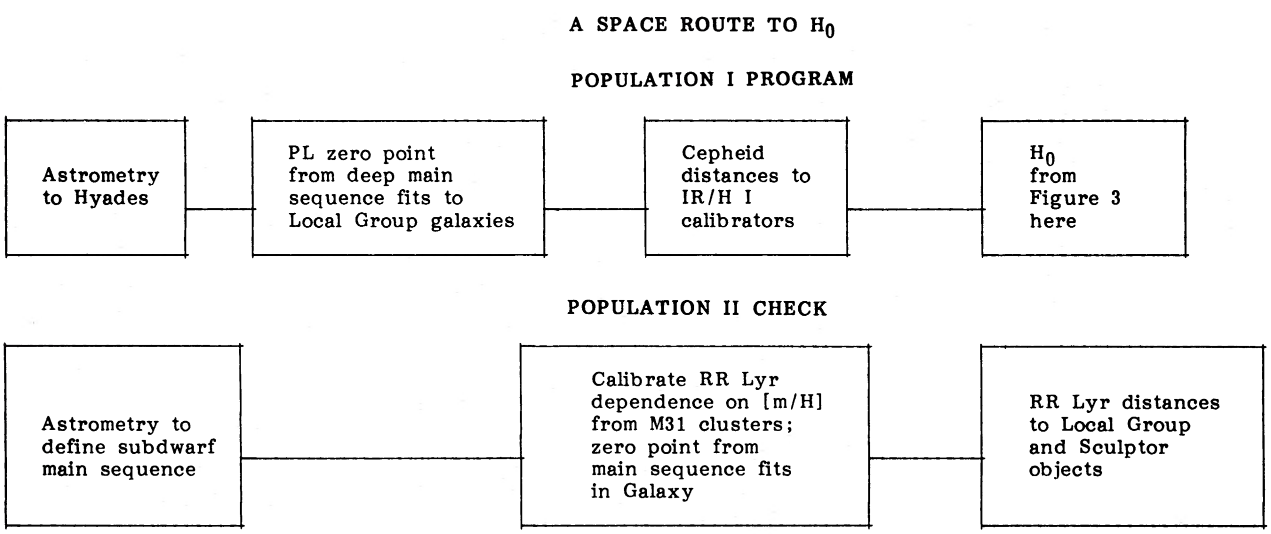

FIG. 4.—Schematic program for determining H_0 with the Hubble Space Telescope

REFERENCES

Aaronson, M., Bothun, G., Mould, J., Huchra, J., Schommer, R. A., and Cornell, M. E. 1986, *Ap. J.*, **302**, 536.
Aaronson, M., Huchra, J., and Mould, J. 1979, *Ap. J.*, **229**, 1.
Aaronson, M., Huchra, J., Mould, J., Schechter, P. L., and Tully, R. B. 1982*a*, *Ap. J.*, **258**, 64.
Aaronson, M., *et al.* 1982*b*, *Ap. J. Suppl.*, **50**, 241.
Aaronson, M., and Mould, J. 1983, *Ap. J.*, **265**, 1.
Aaronson, M., Mould, J., and Huchra, J. 1980, *Ap. J.*, **237**, 655.
Aaronson, M., Mould, J., Huchra, J., Sullivan, W. T., Schommer, R. A., and Bothun, G. D. 1980, *Ap. J.*, **239**, 12.
Balona, L. A., and Shobbrook, R. R. 1984, *M.N.R.A.S.*, **211**, 375.
Blanco, V. M., and Blanco, B. M. 1985, in *Proc. Frascoti Workshop on Population II Variables* (Frascoti: Institute d'Astrofisica Speziale), in press.
Bothun, G. D., Aaronson, M., Schommer, R., Huchra, J., and Mould, J. 1984, *Ap. J.*, **278**, 475.
Burstein, D. 1982, *Ap. J.*, **253**, 539.
Caldwell, J. A. R. 1983, *The Observatory*, **103**, 244.
Chiosi, C., and Pigatto, L. 1985, preprint.
Cohen, J. C. 1985, *Ap. J.*, **292**, 90.
Cornell, M. E., Aaronson, M., Bothun, G. D., and Mould, J. 1984, *Bull. AAS*, **16**, 888.
Cox, J. P. 1985, in *IAU Colloquium 82, Cepheids: Theory and Observations*, ed. B. F. Madore (Cambridge: Cambridge University Press), p. 126.
Davis, M., and Peebles, P. J. E. 1983, *Ann. Rev. Astr. Ap.*, **21**, 109.
de Vaucouleurs, G. 1975, in *Stars and Stellar Systems*, Vol. **9**, *Galaxies and the Universe*, ed. A. Sandage, M. Sandage, and J. Kristian (Chicago: University of Chicago Press), p. 557.
Elias, J. H., Frogel, J. A., Hackwell, J. A., and Persson, S. E. 1981, *Ap. J. (Letters)*, **251**, L13.
Elias, J. H., Frogel, J. A., and Schwering, P. B. W. 1986, *Ap. J.*, **302**, 675.
Fisher, J. R., and Tully, R. B. 1981, *Ap. J. Suppl.*, **47**, 139.
Freedman, W. L. 1985, in *IAU Colloquium 82, Cepheids: Theory and Observations*, ed. B. F. Madore (Cambridge: Cambridge University Press), p. 225.
Frenck, C. S., and White, S. D. M. 1982, *M.N.R.A.S.*, **198**, 173.
Hodge, P. W. 1981, *Ann. Rev. Astr. Ap.*, **19**, 357.
Hopp, U., and Materne, J. 1985, *Astr. Ap. Suppl.*, **61**, 93.
Hubble, E. 1936, *Realm of the Nebulae* (New Haven: Yale University Press).
Humphreys, R. M., Aaronson, M., Lebofsky, M., McAlary, C. W., Strom, S. E., and Capps, R. W. 1985, *A.J.*, submitted.
Humphreys, R. M., and Strom, S. E. 1983, *Ap. J.*, **264**, 458.
Iben, I., and Tuggle, R. S. 1975, *Ap. J.*, **197**, 39.
Kennicutt, R. C. 1979, *Ap. J.*, **228**, 696.
Madore, B. F., and Freedman, W. L. 1985, *A.J.*, **90**, 1104.
Maeder, A. 1983, *Astr. Ap.*, **120**, 113.
Mould, J., Aaronson, M., and Huchra, J. 1980, *Ap. J.*, **238**, 458.
Oepik, E. 1922, *Ap. J.*, **55**, 406.
Rowan-Robinson, M. 1985, *The Cosmological Distance Ladder* (New York: Freeman).
Sandage, A. 1983, *A.J.*, **88**, 1569.
———. 1984, *A.J.*, **89**, 630.
Sandage, A., and Carlson, G. 1983, *Ap. J. (Letters)*, **267**, L25.
Sandage, A., and Tammann, G. A. 1974, *Ap. J.*, **194**, 223.
———. 1985, preprint.
Schmidt, E. G. 1984, *Ap. J.*, **285**, 501.
Schommer, R. A., Olszewski, E. W., and Aaronson, M. 1984, *Ap. J. (Letters)*, **285**, L53.
Thielemann, F.-K., and Truran, J. W. 1985, in *Nucleosynthesis and its Implications on Nuclear and Particle Physics* (5th Moriond Astrophysics Meeting), in press.
Tully, R. B., and Fisher, J. R. 1977, *Astr. Ap.*, **54**, 661.
Uomoto, A., and Kirschner, R. P. 1985, *Astr. Ap.*, **149**, L7.
van den Bergh, S. 1981, *Ap. J. (Letters)*, **248**, L9.
Wagoner, R. V. 1984, *Bull. AAS*, **16**, 1015.
Wheeler, J. C., and Levreault, R. 1985, *Ap. J. (Letters)*, **294**, L17.
Whitmore, B. C. 1984, *Ap. J.*, **278**, 61.

MARC AARONSON: Steward Observatory, University of Arizona, Tucson, AZ 85721

JEREMY MOULD: Caltech/05-24, Pasadena, CA 91101