21 August 1981, Volume 213, Number 4510 SCIENCE

Size and Age of the Universe

Sidney van den Bergh

Summary. The age of the universe based on abundances of isotopes is in the range 10 billion to 15 billion years. This is consistent with the age range 12 billion to 20 billion years calculated from the evolution of the oldest galactic stars. A third estimate of the age of the universe is based on the Hubble relation between the velocities of galaxies and their distances from us, where the inverse of the Hubble parameter H is a measure of the age of a uniformly expanding universe. Evidence that has been accumulating over the past few years indicates that the expansion of the universe may exhibit a rather large local perturbation due to the gravitational attraction of the Virgo supercluster. Different types of observations still produce conflicting evidence about the velocity with which the Local Group of galaxies (of which our Milky Way system is a member) is falling into the Virgo cluster. The results to date indicate that this velocity lies somewhere in the range 0 to 500 kilometers per second. The resulting ambiguity in the flow pattern for relatively nearby galaxies makes values of H derived from galaxies with radial velocities less than 2000 kilometers per second particularly uncertain, and this restricts determinations of H to distant galaxies, for which distances are particularly uncertain. The best that can be said at present is that H^{-1} yields a maximum time scale in the range 10 billion to 20 billion years.

Three lines of evidence suggest that the universe originated as a gigantic exploding fireball:

1) The discovery (*1*) that distant galaxies are all receding from us with velocities that are proportional to their distances.

2) The detection of the 3 K microwave background by Penzias and Wilson (*2*), which represents the redshifted radiation of the primeval fireball that was first predicted by Gamow (*3*).

3) The observed abundances of ^{2}H, ^{3}He, ^{4}He, and ^{7}Li, which are in good agreement (*4*) with the hypothesis that these nuclei were formed from hydrogen in a hot "big bang."

Excellent accounts of early work on the expansion of the universe and the blackbody background radiation are given in Hubble (*5*) and Penzias (*6*), respectively.

Methods for Determining the Age of the Universe

Three quite independent types of evidence are used to estimate the age of the universe: (i) nuclear chronology (*7–9*), (ii) the ages of the oldest stars, and (iii) measurements related to the expansion of the universe.

Nuclear chronology. Intercomparison of the theoretical production rates and observed abundance ratios of ^{244}Pu, ^{238}U, ^{235}U, ^{232}Th, ^{187}Re, and ^{187}Os yield estimates for the mean time interval between the creation of these elements and the formation of the solar system. The main uncertainty results from the fact that the relation between this mean time interval and the time when heavy-element formation started depends on the history of star formation or, more precisely, on the rate at which supernovae produced elements by the r process (rapid neutron capture) (*10*). For star formation in an initial burst this mean time interval will, for example, be twice as long as for formation at a uniform rate.

The best fit to the currently available data (*11*) is given by a model in which r-process elements started forming 6.1 ± 2.3 gigayears (1 Gyr = 10^9 years) before the origin of the solar system at a rate that decayed exponentially with a time scale $T_r = 5.4^{+6.2}_{-3.4}$ Gyr. Since the age of the solar system is now well established at 4.6 Gyr, it follows that galactic star formation started 10.7 ± 2.3 Gyr ago. Allowing some additional time for the collapse of our Galaxy and the formation and evolution of the first stars then yields $A_U \sim 12^{+3}_{-2}$ Gyr for the age of the universe.

Ages of the oldest stars. Globular cluster stars are among the oldest individual objects known in the Galaxy. From the evolutionary tracks of stars in metal-poor globular clusters, Iben (*12*) obtains ages in the range 12.2 to 19.5 Gyr, the exact value depending on the adopted helium abundance Y and heavy-element abundance Z. By fitting calculated evolutionary tracks of metal-poor stars to the observed color-magnitude diagrams of clusters, Demarque (*13*) finds ages of 14 to 16 Gyr for the oldest metal-poor globulars and ~ 10 Gyr for relatively metal-rich clusters. This large age difference is quite unexpected, since canonical models (*14*) predict that the galactic halo will collapse on a gravitational time scale, that is, in ≤ 1 Gyr. In any event, it is reassuring that the age range 10 to 16 Gyr obtained by Demarque brackets the age that Fowler (*11*) and Schramm (*15*) obtain from cosmochronology.

Expansion of the universe. By 1917, radial velocities had become available for 15 galaxies. Wirtz (*16*) first drew attention to the fact that the majority of these objects—12 of the 15—were receding from the sun. In analogy with studies in stellar dynamics, he introduced a K (expansion) term amounting to +656

The author is director of the Dominion Astrophysical Observatory, Herzberg Institute of Astrophysics, National Research Council of Canada, Victoria, British Columbia, Canada V8X 4M6. This article is based on an invited paper presented at the AAAS Annual Meeting in Toronto on 7 January 1981.

0036-8075/81/0821-0825$01.00/0

Table 1. Measurements of the dipole component of anisotropy of the microwave background radiation.

Source	ΔT (mK)	Right ascension, α (hours)	Declination δ (deg)
Princeton group (*19*)	3.78 ± 0.3	11.6 ± 0.2	-12 ± 5
Berkeley group (*20*)	3.6 ± 0.5	11.2 ± 0.5	$+19 \pm 8$
Weighted mean	3.73 ± 0.26	11.54 ± 0.19	-3.3 ± 4.2

kilometers per second to describe the observed motions of the galaxies. Largely through the efforts of V. M. Slipher, the observational material had grown to a total of 44 radial velocities by 1925. Lundmark (*17*) attempted to fit these data by an equation of the form

$$V = K + HD + LD^2 \qquad (1)$$

in which D is the distance of the galaxy. These distances were derived by Lundmark on the assumption that all galaxies have equal diameters. Finally, Hubble (*1*) was able to show that the first and last terms in Eq. 1 are unnecessary and that the data are well represented by the relation

$$V(\text{km sec}^{-1}) = HD\ (\text{megaparsec}) \qquad (2)$$

which is now often referred to as the Hubble law. In this equation H has the "dimension" $(\text{time})^{-1}$; that is, a determination of the numerical value of the Hubble parameter H yields the time scale on which the universe has been expanding. In a uniformly expanding universe with, for example, $H = 100$ km sec^{-1} Mpc^{-1}, $A_U = 10$ Gyr; for $H = 50$ km sec^{-1} Mpc^{-1}, $A_U = 20$ Gyr. In the real universe, which contains a significant amount of matter, the expansion is decelerated by gravitation. Hence H^{-1} yields only an upper limit to the age of the universe.

Unfortunately, the quest for the numerical value of H has proved to be both long and very difficult. The reason for this is, of course, that galaxies are exceedingly distant, so that "standard candles" are dim and "standard yardsticks" have very small angular diameters. A final difficulty is that the "Hubble flow" may not be uniform and isotropic; that is, H itself may be a function of position. A particular danger is that small-scale nonuniformities in the Hubble flow might result in differences between the local and global values of H. This is a particularly disturbing possibility because the numerical value of the Hubble parameter is most easily determined from radial velocities and distances of galaxies that are relatively nearby (closer than the Virgo cluster).

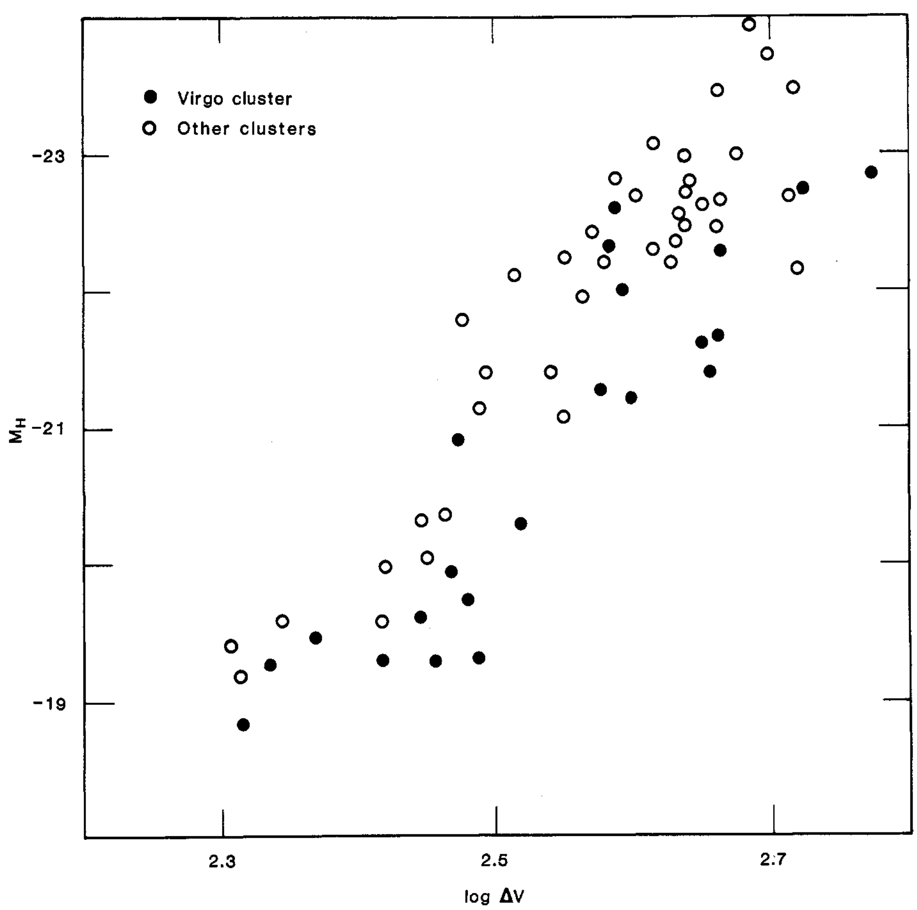

Fig. 1. Plot of infrared absolute magnitudes M_H derived from mean cluster redshifts versus log ΔV. The plot shows that Virgo galaxies of a given ΔV appear fainter than do those in more distant clusters.

Isotropy of the Hubble Flow

Measurements of the cosmic background radiation in opposite directions in space yield slightly different results due to the absolute motion of the sun in space; Peebles (*18*) refers to this motion as the "new aether drift." For small velocities, v, this motion results in a dipole anisotropy of the background microwave radiation of the form

$$T(\theta) \simeq T_0\,[1 + (v/c)\cos\theta] \qquad (3)$$

in which $T_0 \sim 2.7$ K, θ is the angular distance from the apex of motion, and c is the velocity of light. Independent observations of the size and direction of this anisotropy are compared in Table 1. The Princeton data in Table 1 are balloon observations by Boughn *et al.* (*19*), and the Berkeley results are based on U2 aircraft measurements by Gorenstein and Smoot (*20*). The agreement between the results of these two groups is gratifying and greatly strengthens confidence in the reality of the observed effect. The very small formal mean error of the solar apex of motion derived from the data in Table 1 is, however, almost certainly an underestimate of its true value.

From Eq. 3, the mean anistropy given in Table 1 corresponds to a velocity of 414 km sec^{-1} toward a point located only $\sim 16°$ away from the center of the Virgo cluster (*21*), which is situated at $\alpha = 12.42 \pm 0.04$ hours, $\delta = 12.7° \pm 0.4°$ (epoch 1950). Determination of this infall velocity is important because it helps us to map localized deviations from the smooth Hubble flow assumed in Eq. 2. Mapping of such deviations will eventually allow us to relate radial velocities and distances of nearby galaxies. Unfortunately, the near coincidence between the apparent direction of infall and the direction toward the Virgo cluster becomes somewhat less impressive when the infall velocity is corrected for motion of the sun relative to the Local Group of galaxies, of which the Milky Way system is a member. (This correction includes both the motion of the sun relative to the center of the Galaxy and the motion of the Galaxy itself with respect to other galaxies within 1.5 Mpc, to which it is presumed to be gravitationally bound.) Adopting a solar motion (*22*) of 308 km sec^{-1} toward $\alpha = 22.85$ hours, $\delta = +51.4°$ yields an absolute motion for the Local Group of 659 km sec^{-1} toward $\alpha = 11.25$ hours, $\delta = -23.7°$. This apex of motion is located at a distance of $\sim 40°$ from the center of the Virgo cluster. This result shows that the velocity of the Local Group toward the center of the Virgo cluster is comparable to its velocity perpendicular to the direction toward Virgo. It greatly weakens the argument (*23*) that the component of Local Group motion toward the Virgo cluster is entirely due to gravitationally induced infall. This point is discussed in more detail by Matzner (*24*), who proposes that at least part of the observed microwave anisotropy may be due to a global feature of the background radiation that extends approximately to the current event horizon. This suggests that valuable cosmological information could be obtained by comparing the microwave anisotropy with that of x-rays, which must have originated at a more recent epoch.

In principle, through observations of many galaxies with radial velocities less than 10,000 km sec^{-1}, it should be possible to distinguish between infall of the Local Group into the Virgo cluster and translation of the entire Virgo supercluster (including the Local Group and the Virgo cluster) relative to a distant background. Unfortunately, the available data do not yet allow an unambiguous choice between these two alternatives. At present the most promising technique for studying this problem is one developed a few years ago by Tully and Fisher (*25*), who showed that the 21-centimeter line width ΔV (*26*) is closely correlated with galaxy luminosity. More recently Aaronson *et al.* (*27*) argued that infrared M_H (*28*) magnitudes measured at a wavelength of 1.6 micrometers might correlate even more closely with ΔV than the photographic magnitudes M_{pg} used by Tully and Fisher. This is because (i) the uncertain inclination- and type-dependent absorption corrections are much smaller in the infrared than in the blue, (ii) infrared magnitudes are more closely tied to old red stars, which are presumably distributed like the steller mass that governs the (inner) rotation of a galaxy, and (iii) infrared magnitudes are less sensitive to occasional bursts of star formation than are blue magnitudes.

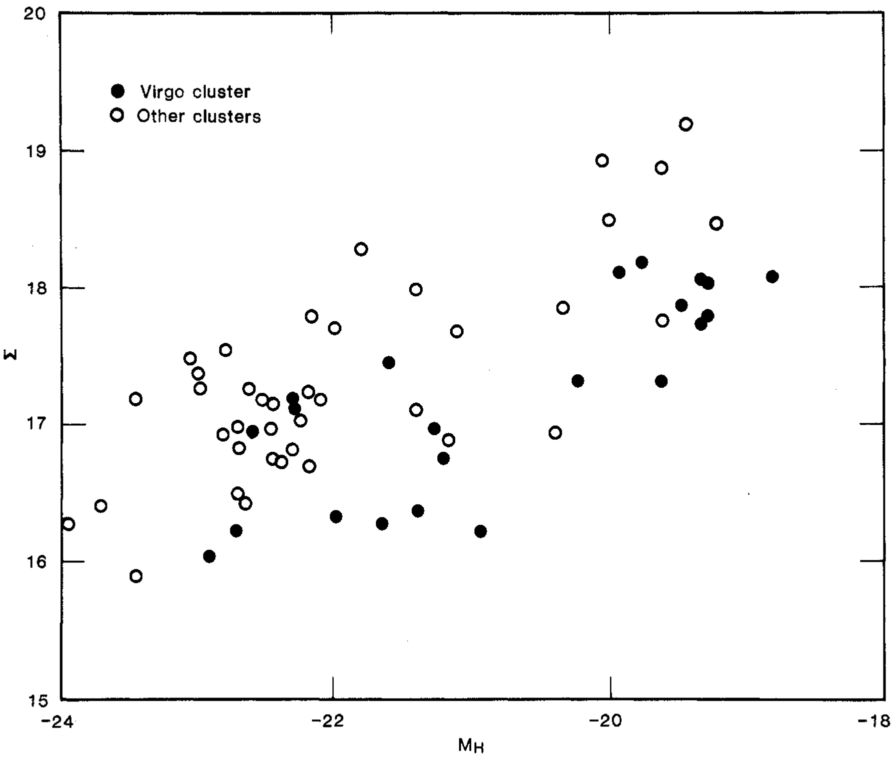

Fig. 2. Infrared surface brightness Σ versus M_H derived from mean cluster redshifts. At a given (distance-independent) surface brightness, Virgo galaxies appear fainter than do those in more distant galaxies.

Figure 1 shows a plot of the absolute infrared magnitude M_H versus line width ΔV for galaxies in the Virgo cluster (*29*) and for four other clusters (*30*) with redshifts that are three to five times greater than that of Virgo. The values of M_H were obtained from the mean cluster velocities, assuming the Hubble relation (Eq. 2) and $H = 100$ km sec^{-1} Mpc^{-1}. Figure 1 shows that the Virgo galaxies are systematically fainter at a given value of ΔV than are the more distant cluster galaxies. This result can be interpreted in one of two ways: (i) at a given luminosity Virgo galaxies rotate faster (are more compact) than those in more distant clusters, or (ii) the distance of the Virgo cluster has been underestimated by Eq. 2 because the Hubble flow is anisotropic. Some support for the first alternative is possibly provided by the observation (*31, 32*) that elliptical galaxies in dense regions are significantly more compact than those in less dense regions. The fact that the dense Virgo cluster and the low-density Ursa Major group appear to exhibit the same M_H versus ΔV relation, however, militates against this suggestion. Aaronson *et al.* (*30*) adopt the second alternative and find that the apparent difference between the M_H versus ΔV relations can be accounted for by assuming that the Local Group has a component of motion of 480 ± 75 km sec^{-1} toward the Virgo cluster. This value is in excellent agreement with the result obtained from the anisotropy of the microwave background but conflicts with that derived from the observations of absolute magnitude versus 21-cm line width discussed by de Vaucouleurs and co-workers (*33, 34*). Figure 2 shows a plot of M_H against the surface brightness Σ of galaxies, defined as

$$\Sigma = H - 5 \log a \qquad (4)$$

in which a (*35*) is the major axis diameter of the galaxy, corrected for absorption and inclination, and H is the apparent infrared galaxy magnitude. Figure 2 shows that Virgo galaxies appear to be less luminous than more distant galaxies with the same Σ. This effect is in the same sense as that shown in Fig. 1 and indicates that the velocity width ΔV, which involves an often uncertain inclination correction, is not responsible for the apparent difference between Virgo and background cluster galaxies in Fig. 1. Figure 3 shows that the Σ versus ΔV relationship does not differ significantly between the Virgo cluster and the more distant clusters observed by Aaronson *et al.* (*30*).

Recent determinations of the infall velocity of the Local Group toward the Virgo cluster, after correction for the

Table 2. Recent determinations of the infall velocity toward the Virgo cluster after correction for solar motion.

Source	Method	Infall velocity (km sec^{-1})
Sandage and Tammann (*51*)	Luminosity classifications and H II region diameters of spirals	−39 ± 162
Kormendy (*52*)*	Surface brightness versus scale size of elliptical galaxies	−39 ± 114
Tammann *et al.* (*53*)	Luminosity classifications of spirals	+60 ± 132
Aaronson *et al.* (*30*)	Fisher-Tully relation for spirals in infrared	+480 ± 75
De Vaucouleurs and Peters (*34*)†	Motion of spirals with optically determined distances	+231 ± 50
De Vaucouleurs *et al.* (*33*)‡	Fisher-Tully relation for spirals in blue	+241 ± 50
Tonry and Davis (*54*)	Absolute magnitude versus velocity dispersion relation:	
	Ellipticals	+470 ± 75
	S0 galaxies	+416 ± 90
Schechter (*55*)	Absolute magnitude versus velocity dispersion in ellipticals	+190 ± 130
This article§	Type I supernovae	+260 ± 145
This article‖	Microwave background	+500 ± 50

*Kormendy (*56*) now believes that his sample of background galaxies may have been contaminated by members of the Virgo supercluster. †Motion toward a point located 25° northeast of the Virgo cluster. ‡Motion toward a point located 18° northeast of the Virgo cluster. §Assuming no incompleteness for distant supernovae. ‖Directed toward a point located 40° southwest of the Virgo cluster.

velocity of the sun relative to distant objects, are given in Table 2. The first three entries in this table should, perhaps, be regarded as having only historical significance. The agreement between individual observations is, unfortunately, still poor. Resolving these discrepancies is one of the highest present priorities of extragalactic astronomy.

In summary, it appears that the Local Group is falling into the Virgo cluster with a velocity that might lie anywhere in the range from slightly more than 0 km sec^{-1} up to 500 km sec^{-1}. The most recent determinations of the infall velocity possible favor values that are approximately half of the aether drift velocity derived from the microwave background. The difference between the aether drift velocity and the infall velocity toward the Virgo cluster might be due to a very local velocity perturbation or a motion of the entire Virgo supercluster, or both. As a result of these uncertainties, the relationship between the local and global values of the Hubble parameter remains uncertain at the ~ 30 percent level.

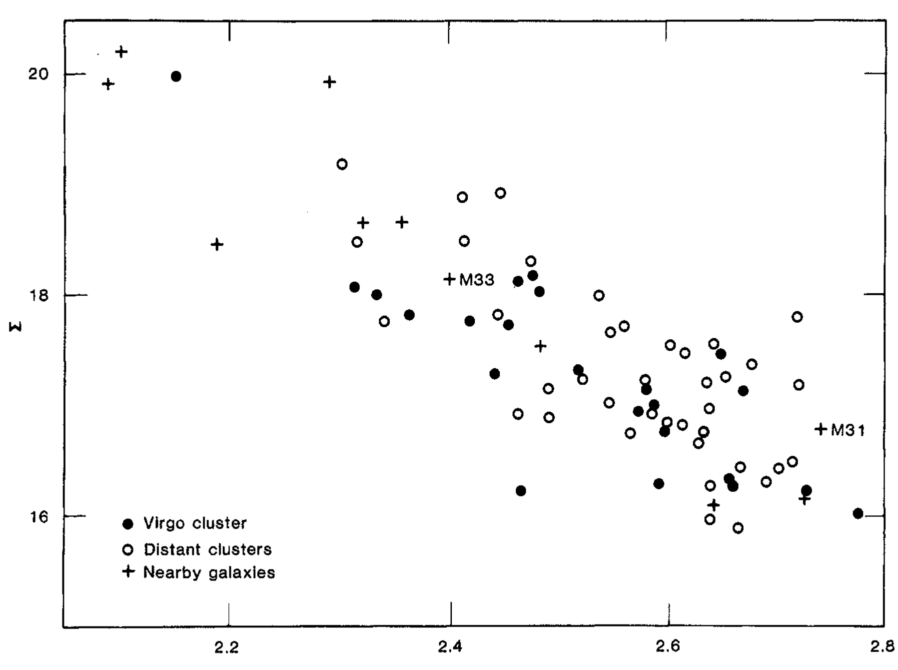

Fig. 3. Plot of infrared surface brightness Σ of galaxies versus corrected hydrogen line width log ΔV. Within the accuracy of the present data, the Σ versus log ΔV relationship is the same for the Virgo cluster, for galaxies in more distant clusters, and for nearby galaxies observed by Aaronson *et al.* (*27*).

Determination of the Hubble Parameter

In view of the huge uncertainties introduced by the possible anisotropy of the Hubble flow within the Virgo supercluster, it seems prudent to restrict determinations of the Hubble parameter H to regions with redshifts >> 1000 km sec^{-1}. At such large distances it is, unfortunately, no longer possible to use precision distance indicators such as Cepheids and novae. This leaves us with only supernovae and the integral properties of galaxies as potential distance calibrators.

Tully-Fisher effect. In their original paper Tully and Fisher compared the hydrogen line widths with blue galaxy magnitudes, which might be strongly affected by bursts of star formation and by uncertain corrections for absorption. Such problems are greatly reduced if, following Aaronson *et al.* (*27*), infrared rather than blue magnitudes are used. The data by Aaronson *et al.* (*30*) for four distant clusters with redshifts in the range $4000 < V < 5900$ km sec^{-1} yield the relation

$$-21.9 - M_H - 5\log(H/100) = (10.5 \pm 0.7)(\log \Delta V - 2.57) \quad (5)$$

if measurements of ΔV are assumed to be error-free. Substitution of the known values of M_H and ΔV for M31, M33, and the Galaxy into Eq. 5 yields determinations of the global Hubble parameter. In view of the uncertainty in the distance of the M81 group (*36*) it seems prudent not to attempt to calibrate H with galaxies located outside the Local Group.

1) M31 (Andromeda): Using the old Hyades distance modulus (*37*), the distance to the Andromeda nebula is 630 kiloparsecs. Recent work by McClure (*38*) suggests that this Hyades distance needs to be increased by ~ 25 percent. Van den Bergh (*39*) shows that only about half of this increase will be reflected in the extragalactic distance scale because some distance indicators (novae, RR Lyrae stars) do not depend on the Hyades distance. We shall therefore adopt a distance of ~ 705 kpc. At this distance the apparent infrared magnitude of M31 measured by Aaronson *et al.* (*27*) corresponds to $M_H = -23.3$ for M31. Substituting this value and $\Delta V = 552$ km sec^{-1} into Eq. 5 yields $H = 83$ km sec^{-1} Mpc^{-1}.

From a comparison of M31, whi :h is of Hubble type Sb and luminosity class I-II, with distant SbI and SbII galaxies with known redshifts, Stenning and Hartwick (*40*) find $H = 75 \pm 15$ km $\sec^{-1}$ Mpc^{-1}, which transforms to $H = 69 \pm 14$ km $\sec^{-1}$ Mpc^{-1} for the M31 distance scale used in this article.

2) M33: Following the procedures outlined above, the distance to M33 becomes ~ 715 kpc. With an apparent infrared magnitude determined by Aaronson *et al.* (*27*) this yields $M_H = -19.9$. Substituting this value and $\Delta V = 253$ km $\sec^{-1}$ yields a Hubble parameter $H = 89$ km $\sec^{-1}$ Mpc^{-1}.

3) The Galaxy: De Vaucouleurs and Pence (*41*) estimated that the Galaxy has an absolute blue magnitude M_T^0 $(B) = -20.1$. From the data given by Aaronson *et al.* (*30*), it is found that galaxies of type SbcII have a blue minus infrared color index $B - H \simeq 2.5 \pm 0.3$, so that M_H (Galaxy) $\simeq -22.6 \pm 0.3$. Unfortunately, the galactic rotational velocity near the sun $V_0 \simeq 0.5\ \Delta V$ is not well known. Table 3 shows that the Hubble constant that is derived from Eq. 5 and the value of M_H obtained above depends critically on the assumed value of V_0. If a galactic rotational velocity of 220 km $\sec^{-1}$ (*42*) is adopted, the Galaxy is moving (relative to the Local Group as a whole) toward galactic longitude $\ell \sim 145°$ and latitude $b \sim -20°$ with a velocity of ~ 115 km $\sec^{-1}$. This direction is close to that of M31 ($\ell = 121°$, $b = -22°$); that is, the Galaxy may be falling toward the Andromeda nebula (*43*).

Table 3. Dependence of Hubble parameter on rotational velocity of the Galaxy.

V_0 (km $\sec^{-1}$)	H (km $\sec^{-1}$ Mpc^{-1})
200	118
250	74
300	50

Table 4. Absolute magnitudes of type I supernovae at maximum light.

Sample	$\langle M_B(\max)\rangle$*	N†
Virgo cluster	-17.93 ± 0.23	9
Field ($V < 1600$ km $\sec^{-1}$)	-17.72 ± 0.18	17
Coma cluster	-18.42 ± 0.11	5
Field ($V > 1600$ km $\sec^{-1}$)	-18.60 ± 0.12	16

*From Branch and Bettis (*50*) fpr $H = 100$ km $\sec^{-1}$ Mpc^{-1}. †Number of observations.

Comparison of Virgo and Coma Clusters

The Coma cluster (*44*) has a redshift $\langle V_0\rangle = 6947 \pm 123$ km $\sec^{-1}$ and Virgo has a redshift $\langle V_0\rangle = 1057 \pm 52$ km $\sec^{-1}$ (*45*). For a pure Hubble flow these values correspond to a distance ratio of 6.6 ± 0.3 and hence a difference in distance modulus $\Delta = 4.1$. For an infall velocity of 500 km $\sec^{-1}$ toward Virgo this distance ratio reduces to 4.8 and hence $\Delta = 3.4$. The latter value agrees well with the value $\Delta = 3.5 \pm 0.2$ which Aaronson *et al.* (*46*) obtained by intercomparison of the luminosity versus ultraviolet minus yellow color relations for early-type galaxies in Virgo and Coma. Confidence in this result is, however, reduced by the observation that the luminosity versus ultraviolet minus infrared and luminosity versus yellow minus infrared color relations yield $\Delta = 3.0 \pm 0.2$ and $\Delta = 2.6 \pm 0.3$, respectively. These results show that early-type galaxies in Coma must have intrinsically different colors from those in Virgo. In particular, Aarsonson *et al.* (*46*) suggest that Virgo galaxies of a given luminosity might be brighter in the infrared than those in Coma because they contain either stars that are more metal-rich or very red giants of intermediate age.

From a comparison of the luminosity versus ultraviolet minus blue ($U - B$) color relations of early-type galaxies in Virgo and Coma, Sandage (*47*) obtains $\Delta = 3.66 \pm 0.14$, which is consistent with the value obtained by Aaronson *et al.* (*46*). Confidence in the universality of the luminosity versus $U - B$ color relation for early-type galaxies is, however, shaken by the fact that its application (after calibration in the Local Group) to Coma yields $H \simeq 170$ km $\sec^{-1}$ Mpc^{-1}. This result shows that color–absolute magnitude relationships for early-type galaxies are not universal. Values of the distance scale derived from them are therefore suspect.

Another possible approach is to compare NGC 4472, the brightest galaxy in Virgo, with the first ranked galaxies in distant clusters. Such a comparison has been carried out by Aaronson and Mould (*48*). These authors find that NGC 4472 lies within the magnitude range of distant giant ellipticals if the infall velocity of the Local Group is less than 300 km $\sec^{-1}$. For an infall velocity of 500 km $\sec^{-1}$ NGC 4472 lies ~ 2 standard deviations above the ridge line of the Hubble diagram defined by the brightest cluster galaxies. It is concluded that application of the first brightest cluster galaxy method favors a low value of the infall velocity but does not entirely exclude a value as large as 500 km $\sec^{-1}$.

Supernovae. Because of their high luminosities, supernovae would, at first sight, appear to be ideal calibrators of the extragalactic distance scale. In practice, they are of only limited usefulness because no good local calibrators are available. The supernovae of 1054 (Crab) and 1885 (M31) have relatively well-determined maximum luminosities, but their type assignments are uncertain. For the well-established type I supernovae of 1006 (Lupus), 1572 (Tycho), and 1604 (Kepler) the maximum luminosities are uncertain because of uncertain distances or because their magnitudes at maximum light are not well established. Finally, the type II supernova of 1667 (Cassiopeia A) was not observed at maximum and was, in any case, probably atypical.

Perhaps the most straightforward method for determining the absolute magnitudes of supernovae is provided by the assumption that the shells of expanding supernovae may, during the first few weeks of their expansion, be modeled as expanding spherical blackbodies. From this assumption and color and radial velocity observations of supernovae of type I, Branch (*49*) obtains $\langle M_B(\max)\rangle = -20.25 \pm 0.31$, in which $M_B(\max)$ is the maximum absolute magnitude in blue light. It should, however, be emphasized that the model adopted by Branch is probably oversimplified. Concepts such as position of the photosphere may not be as straightforward as they appear at first sight. Unfortunately, all supernovae for which detailed color and radial velocity information is presently available are nearby objects that lie within the local velocity anisotropy. They do not, therefore, provide independent information on the global value of the Hubble parameter.

Data on the observed magnitudes of type I supernovae, taken from a compilation of Branch and Bettis (*50*), are listed in Table 4. The table shows what appears to be a significant difference in $\langle M_B(\max)\rangle$ for nearby Virgo and field galaxies with radial velocities $V < 1600$ km $\sec^{-1}$ and distant galaxies in the Coma cluster and in the field with $V > 1600$ km $\sec^{-1}$. This difference could be due to either (i) greater incompleteness of the Coma and distant field sample at faint magnitudes or (ii) infall of the Local Group toward Virgo with a velocity of ~ 260 ± 145 km $\sec^{-1}$.

For distant field galaxies Table 4 shows that

$$\langle M_B(\max)\rangle - 5 \log (H/100) = -18.60 \pm 0.12 \qquad (6)$$

Substituting $\langle M_B(\max)\rangle = -20.25$ (*41*) into Eq. 6 yields $H = 47 \pm 7$ km $\sec^{-1}$ Mpc^{-1}.

Conclusion

A number of different studies have been made of the Hubble flow in nearby regions of space. These investigations yield conflicting results, which indicate that the velocity with which the Local Group is falling into the Virgo cluster may lie anywhere in the range 0 to 500 km sec^{-1}.

Reconciling these discrepant results on the local anisotropy of the Hubble flow is one of the most urgent problems facing contemporary extragalactic astronomy. Until the local flow pattern is better understood, determinations of the Hubble parameter H will have to be derived from exceedingly difficult studies of distant galaxies with redshifts $\geqslant 1000$ km sec^{-1}. Presently available data indicated that $50 < H < 100$ km sec^{-1} Mpc^{-1}. The corresponding expansion time scale for the universe lies in the range 10 to 20 Gyr. This range brackets ages derived from nuclear chronology and age estimates for the oldest known stars. More accurate determinations of the global value of H and local deviations from it promise to provide valuable new information on the density of the universe, the deceleration of its expansion, and possibly on the size of the cosmological constant.

References and Notes

1. E. P. Hubble, *Proc. Natl. Acad. Sci. U.S.A.* **15**, 168 (1929).
2. A. A. Penzias and R. W. Wilson, *Astrophys. J.* **142**, 419 (1965).
3. G. Gamow, *Phys. Rev.* **70**, 572 (1964).
4. R. V. Wagoner, *Astrophys. J.* **179**, 343 (1973).
5. E. Hubble, *The Realm of the Nebulae* (Yale Univ. Press, New Haven, Conn., 1936).
6. A. A. Penzias, in *Cosmology, Fusion and Other Matters*, F. Reines, Ed. (Colorado Associated Univ. Press, Boulder, 1972), p. 29.
7. W. A. Fowler, *Robert A. Welch Found. Conf. Chem. Res.* **21**, 61 (1977).
8. K. L. Hainebach and D. N. Schramm, *Astrophys. J.* **212**, 347 (1977).
9. E. M. D. Symbalisty and D. N. Schramm, *Rep. Prog. Phys.*, in press.
10. E. M. Burbidge, G. R. Burbidge, W. A. Fowler, F. Hoyle, *Rev. Mod. Phys.* **29**, 547 (1957).
11. W. A. Fowler, lecture given at the Dominion Astrophysical Observatory, 1 October 1980.
12. I. Iben, paper presented at the AAAS Annual Meeting, Toronto, 5 January 1981.
13. P. Demarque, *Int. Astron. Union Symp.* *85* (1980), p. 281.
14. O. J. Eggen *et al.*, *Astrophys. J.* **136**, 748 (1962).
15. D. N. Schramm, paper presented at the AAAS Annual Meeting, Toronto, 5 January 1981.
16. C. Wirtz, *Astron. Nachr.* **206**, 109 (1918).
17. K. Lundmark, *Mon. Not. R. Astron. Soc.* **85**, 865 (1925).
18. P. J. E. Peebles, *Physical Cosmology* (Princeton Univ. Press, Princeton, N.J., 1971).
19. S. P. Boughn, E. S. Cheng, D. T. Wilkinson, *Astrophys. J. Lett.* **243**, L113 (1981).
20. M. V. Gorenstein and G. F. Smoot, *Astrophys. J.* **244**, 361 (1981).
21. S. van den Bergh, *Vistas Astron.* **21**, 71 (1977).
22. A. Yahil, G. A. Tammann, A. Sandage, *Astrophys. J.* **217**, 903 (1977).
23. M. Davis, J. Tonry, J. Huchra, D. W. Latham, *Astrophys. J. Lett.* **238**, L113 (1980).
24. R. A. Matzner, *Astrophys. J.* **241**, 851 (1980).
25. R. B. Tully and J. R. Fisher, *Astron. Astrophys.* **54**, 661 (1977).
26. This is the line width at 20 percent of maximum intensity corrected for galaxy inclination, which is designated $\Delta V_{20}(0)$ by Aaronson *et al.* (*27*).
27. M. Aaronson, J. Mould, J. Huchra, *Astrophys. J.* **137**, 655 (1980).
28. This is the fully corrected magnitude, which Aaronson *et al.* (*27*) call $H^c_{-0.5}$.
29. J. Mould, M. Aaronson, J. Huchra, *Astrophys. J.* **238**, 458 (1980).
30. M. Aaronson *et al.*, *ibid.* **239**, 12 (1980).
31. K. M. Strom and S. E. Strom, *Astron. J.* **83**, 73 (1978).
32. S. E. Strom and K. M. Strom, *ibid.*, p. 732.
33. G. de Vaucouleurs, W. L. Peters, L. Bottinelli, L. Gougenheim, G. Paturel, preprint.
34. G. de Vaucouleurs and W. L. Peters, preprint.
35. This is D_1 in Aaronson *et al.* (*30*).
36. B. F. Madore, *Mon. Not. R. Astron. Soc.* **177**, 157 (1976).
37. S. van den Bergh, *Int. Astron. Union Colloq.* *37* (1977), p. 14.
38. R. D. McClure, *Bull. Am. Astron. Soc.* **12**, 867 (1981).
39. S. van den Bergh, *Astrophys. J. Lett.* **215**, L103 (1977).
40. M. Stenning and F. D. A. Hartwick, *Astron. J.* **85**, 101 (1980).
41. G. de Vaucouleurs and W. D. Pence, *ibid.* **83**, 1163 (1978).
42. C. S. Frenk and S. D. M. White, *Mon. Not. R. Astron. Soc.* **193**, 295 (1980).
43. F. D. Kahn and L. Woltjer, *Astrophys. J.* **130**, 705 (1959).
44. S. A. Gregory and L. A. Thompson, *ibid.* **222**, 784 (1978).
45. J. W. Sulentic, *ibid.* **241**, 67 (1980).
46. M. Aaronson, S. E. Persson, J. A. Frogel, Steward Observatory preprint 295 (1980).
47. A. Sandage, *Astrophys. J.* **176**, 21 (1972).
48. M. Aaronson and J. Mould, Steward Observatory preprint 300 (1980).
49. D. Branch, *Mon. Not. R. Astron. Soc.* **179**, 401 (1977).
50. D. Branch and C. Bettis, *Astron. J.* **83**, 224 (1978).
51. A. Sandage and G. A. Tammann, *Astrophys. J.* **196**, 313 (1975).
52. J. Kormendy, *Int. Astron. Union Colloq.* *37* (1977), p. 155.
53. G. A. Tammann, A. Yahil, A. Sandage, *Astrophys. J.* **234**, 775 (1979).
54. J. L. Tonry and M. Davis, *ibid.*, in press.
55. P. L. Schechter, *ibid.* **85**, 801 (1980).
56. J. Kormendy, private communication.

Molecular and Cellular Mechanisms of Leukocyte Chemotaxis

Ralph Snyderman and Edward J. Goetzl

Nearly 100 years ago, Eli Metchnikoff noted that coelomic cells accumulated rapidly around a rose thorn that he had placed through the skin of a transparent starfish larva (*1*). Metchnikoff's hypothesis that the cells which had responded to the foreign body functioned to defend the host provided the cornerstone for our current understanding of the role of phagocytic leukocytes in cellular immune responses and inflammatory reactions. The contention that chemical mediators evoked the directed migration of leukocytes led Pfeffer in 1884 to utilize the term chemotaxis and stimulated Leber several years later to speculate that phagocytic leukocytes could sense and follow concentration gradients of specific stimuli (*2*). In prokaryotic cells chemotaxis is a means of finding nutrients, whereas in more complex animals, such as man, it is a process by which cells of the immune system become localized at sites of inflammation. The biochemical mechanisms of bacterial chemotaxis are relatively well defined (*3*). The application of the techniques of modern chemistry and cellular biology to the study of leukocyte function has recently permitted rapid advances in this field as well. Several classes of chemotactic factors have been defined, and cytostructural as well as a number of biochemical prerequisites of leukocyte chemotactic responses have been elucidated.

The ability to quantify the migration of leukocytes in vitro by reproducible techniques has fostered significant advances in the understanding of chemotaxis. In 1962, Boyden (*4*) observed that polymorphonuclear leukocytes (PMN's) placed

Dr. Snyderman is Director of the Laboratory of Immune Effector Function of the Howard Hughes Medical Institute and the Division of Rheumatic and Genetic Diseases at Duke University, and Professor of Medicine and Immunology at Duke University Medical Center, Durham, North Carolina 27710; Dr. Goetzl is Director of the Howard Hughes Medical Institute Immunology Laboratories at Harvard Medical School, and Associate Professor of Medicine in the Departments of Medicine, Harvard Medical School and Robert B. Brigham Division of the Brigham and Women's Hospital, Boston, Massachusetts 02115.