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Hubble's Variable Parameter: the Long and Short of It

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The "constant" H , whose customary units are (km/sec)/Megaparsecs, is a measure of the distance scale, expansion rate, and (indirectly) age of the universe. The first determinations of its value, by Hubble himself, between 1929 and 1936, were in the range 500-550 km/sec/Mpc, implying a universe only about 2 Gyr old (less than the age of the earth as understood even then). In a series of quick steps from 1952 to 1975, the best value dropped from 500 to 250 to 125 to 50-100 km/sec/Mpc. And there it has remained ever since, with a factor of two uncertainty. The continuing discrepancies among values found by different workers using different methods are an inconvenience to the entire astronomical community, because the value of H enters into our determinations of masses and luminosities of distant objects, of the fraction of the closure density of the universe that can be present in ordinary baryonic matter, and many other things we would like to know. It is not clear that the issue will be firmly resolved in the near future, despite the ever-increasing rate of publications on the subject.

1. INTRODUCTION: THE SIGNIFICANCE OF THE HUBBLE PARAMETER

Hubble's constant is the ratio of redshift to distance of galaxies whose distances from us are in the range 30-1000 Megaparsecs (far enough away to wash out variations due to random velocities, but close enough that deviations from a linear relation are small). Its units are reciprocal time (generally expressed as (km/sec)/Mpc). The other standard parameters of cosmology, the deceleration parameter q , the density ρ , and the cosmological constant Λ are closely related in the standard, general relativistic (Friedmann-Robertson-Walker) models of the universe, for instance

$$H^2 q = \frac{4\pi G \rho}{3} - \frac{\Lambda c^2}{3} \quad (1)$$

There are good observational and theoretical reasons to reject explanations of the linear redshift-distance relationship other than overall expansion of the universe, though a very few defenders of tired light, explosions into existing space-time, or de Sitter solutions still flourish.

The numerical value of the Hubble constant enters into the numbers we derive from observations for many important quantities. If we parametrize

our ignorance with $h = H/100$, then luminosities scale as h^{-2} , masses (from dynamical arguments that say $M \approx v^2 R/G$) scale as h^{-1} , Mass-to-light ratios as h , the closure density of the universe as h^2 , and the apparent luminosity density as h . Since nucleosynthesis considerations limit the baryon-to-photon ratio of the universe, the maximum possible fractional density in baryonic material scales as h^{-2} . And, finally, the expansion time scale depends on h^{-1} (whose range is 10-20 Gyr for $H = 50-100$ km/sec/Mpc). The actual total age of the universe will range between $2/3$ and $4/3$ of h^{-1} for values of ρ and Λ permitted by other considerations.

2. DISTANCE-INDICATORS: THE PRACTICAL ASTRONOMER'S GUIDE TO MEASURING H

Given a sufficiently large telescope and sufficiently sensitive photon detectors, you can measure a redshift for any astronomical object blessed with sharp spectral features. Meaningful redshifts for cosmological purposes range from about 0.03 to 4.9, and larger values keep turning up. The hard part is figuring out the distances to the objects. Current distance indicators can be divided into five categories: (a) Knowing the real

luminosity in erg/sec of something whose apparent brightness you measure in erg/sec/cm², (b) Knowing the real physical size in meters of something whose angular size on the sky you can measure in arcsec, (c) Knowing the real physical velocity in km/sec of something whose angular motion on the sky you can measure in arcsec/year, (d) Measuring the ratio of two properties of an object that depend on different powers of distance, and (e) Voodoo. There are non-controversial examples of methods of types a, b, and c within the realm of stellar astronomy (but none of types d and e). There have also been spectacular failures arising from neglect of some vital piece of physics (like absorption of star light by interstellar dust and the domination of flux-limited samples by intrinsically bright objects). A second, orthogonal cut of methods depends on whether they can be (1) directly calibrated by geometrical methods or main sequences of star clusters, (2) secondarily calibrated on standards of type (1), or (3) independently calibrated by some physical understanding.

Type (a) indicators or standard candles currently in use include, by calibration type, (1) RR Lyrae stars, Cepheid variables, planetary nebulae, novae, brightest stars, (2) globular cluster luminosity functions or specific frequencies, brightest members of clusters of galaxies (the only standard "ladder" item at redshifts greater than 0.05), supernovae, and (3) supernovae, especially Type Ia.

Type (b) or standard meter stick indicators include (1) sizes of HII regions, separations of spiral arms, and spiral disk scale lengths, (2) scale lengths, and (3) variability of lensed quasars. Type (c) or velocity methods include only type 3 calibrations, the Baade-Wesselink method applied to variable stars and supernovae (integration of changing radial velocity = change in size), the light echo rings around SN 1987A, and the radial velocities and proper motions of H₂O masers in galactic nuclei (a promising method for the future).

Ratio type methods, (d) include surface brightness fluctuations arising from Poisson-like variations in numbers of stars contributing to the brightness of particular bits of galaxies, mass-to-

light ratios (first applied by Ernst Öpik in 1922 to the case of M31), and the Sunyaev-Zeldovich effect, in which photons of the microwave background are scattered out of the line of sight by hot electrons that simultaneously emit X-rays (the missing 3K flux and the observed X-ray flux depend on different combinations of electron density and distance). All of these require you to understand the underlying physics of objects and processes and so are of type 3, otherwise known (insultingly) as "model dependent".

Finally, there are type (e) indicators with type (2) calibrations on Cepheid variables and such. These include the Tully-Fisher relation between rotation speed and optical luminosity of disk galaxies and the relationship between effective diameter and velocity dispersion in elliptical galaxies (roughly the Faber-Jackson relation). Although these yield quite tight correlations, the underlying physics is not even slightly understood.

3. PUBLISHED VALUES OF H

Early determinations relied upon luminosities for Cepheid variables that were substantially wrong, owing to the neglect of interstellar light absorption. Fernie (1969) has told the story of how this was slowly and painfully sorted out. H dropped a factor of two in 1952 when Walter Baade and David Thackeray, speaking at the IAU general assembly in Rome, reported that, respectively, they could not and could see the RR Lyrae stars in Andromeda and the Magellanic Clouds. Allan Sandage and his collaborators took further steps downward, based on the recognition that some objects previously interpreted as single stars were really compact clusters and illuminated gas (HII regions). Sidney van den Bergh entered the fray in 1960 (see van den Bergh 1994 for his outline of history), and Gerard de Vaucouleurs in the mid 1960's (see, e.g., de Vaucouleurs 1982 and Sandage 1995 for their tales). Soon after, it became clear that the workers mentioned so far had polarized between $H = 50$ (Sandage, Gustave Tammann and their colleagues) and $H = 80-100$ (van den Bergh, de Vaucouleurs, and their co-workers).

Kennicutt et al. (1995) show several amusing plots of Hubble constants published between 1975 and early 1995, including a division by author. There are nearly 100, many of whose error bars do not overlap many of the others. Removing all values published by Sandage and Tammann and by de Vaucouleurs reduces the numbers of points near the extremes but does not reduce the total occupied range. Table 1 provides similar information over a narrower time window, including the methods used and the error bars where the authors admit to the possibility of error. A few were published as firm upper or lower limits.

Published values in the last decade closely pack the range from 45 to 100 km/sec/Mpc. The polarization between senior workers has, however, led many of us to think along the lines of a “short” and a “long” distance scale. The former goes with large values of H (such that it is genuinely quite difficult to force the universe to be as old as stars in globular clusters say they are), and the latter with small values of H (less constraining, especially if you do not insist that the cosmological constant and curvature constants of the universe both be zero). Careful examination of key papers from the various groups indicates some deviation in distance scales even very close to us – are the Hyades at a distance modulus of 3.15 or 3.33; do we live more like 7 or 10 kpc from the center of our own galaxy; and is neighbor Andromeda at 650,000 or 900,000 pc? More than half the disagreement has accumulated by the distance of the Virgo cluster (12.8 or 21 Mpc?) and the rest a bit further beyond.

4. CONTRIBUTORS TOWARD THE LONG/SHORT DIVERGENCE AND THE NATURE OF A GOOD DISTANCE INDICATOR

The first step in establishing a cosmic distance ladder is getting out of the Milky Way. This means correcting for absorption by dust therein, and here arises the first long/short disagreement: is the absorption toward the galactic poles along the lines of sight to galaxies and clusters used in measuring H 0.2–0.3 magnitudes or vanishingly small? If absorption is important, then a faintish

galaxy is faint partly because its light is being absorbed, and not just because it is a long ways away.

Next one has to allow for physical motions of our own and other galaxies that are not due to smooth, cosmic expansion. The obvious, nearby, one is the gravitational effect of the massive Virgo cluster of galaxies. The observed result is customarily called “Virgocentric infall”. This does not mean that we are really falling toward the Virgo cluster. Rather, we and it are moving apart from each other, but not as fast as would be the case without the local mass concentration. “Short” people think the difference is 200–300 km/sec, and “long” people that it is only about 100 km/sec. This matters when you move to larger distances, even supposing you know the distance to Virgo. Is the right velocity (without distortions) for its distance 1150 or 1350 km/sec?

The third large contributor to the divergence of the two scales is Malmquist bias. Gunnar Malmquist (1893–1982) is remembered by cosmologists for a pair of papers published in 1920 and 1924, pointing out that deriving the real average properties of a class of astronomical objects is not as simple as you think it is going to be. The bias itself is an example of the Ehrenfest effect (“It is difficult to explain something, even when you understand it...”), but here goes.

What you really want to know about a given standard candle (or meter stick) is the average brightness of the class of object you are looking at in some representative volume centered around you. Then you can compare that average to the average apparent brightness of the same class of object far away, and voila, H reveals itself. But the dots and smudges of light in the sky that we call stars and galaxies do not come labeled with their distances (in fact, these days, the skies are so bright near large cities that you can’t even read the names of the constellations). Rather, you collect a data sample consisting of all the objects that look brighter (and perhaps bigger) than some limit set by your telescope, your detector, or your grant. This is called a flux limited sample.

Flux limited samples are very complete for the nearest objects, but include only the intrinsically most luminous of distant ones. Thus, if you for-

get to allow for Malmquist bias, you will conclude that your large redshift galaxies look pretty bright on average because they are pretty close. Correcting for the bias means saying that they look bright partly because you are average only over the bright wing of the total luminosity distribution and not over the whole thing. Proper correction requires measuring the real distribution function for your tracer objects at many different distances, including the biggest one you want to use. It can't be done (unless you have a bigger telescope, better detectors, or a larger grant). Instead, you measure the distribution nearby, and hope that the dispersion is the same everywhere. "Long" distance scale people have concluded that the necessary Malmquist correction for brightest cluster galaxies and other standard candles is large. "Short" people think it is small.

Thus we can say that the ideal distance indicator has the following properties: (1) very bright so that you can see examples out beyond local deviations from smooth Hubble flow, which may extend to $100 h^{-1}$ Mpc or more (and if we live in an over-dense region of the universe, the local H will be bigger than the global one), (2) common, so that you have lots of objects to average over, (3) both well calibrated and physically understood, so that you can say with confidence that you know Cepheids in M100 and supernovae at $z = 0.3$ have the same brightnesses (etc.) as local ones, and (4) a very small range of real brightnesses, so that Malmquist correction will be small. It is not clear that there are any such objects in the universe.

5. LOOKING AHEAD

In two years of deliberation that led up to the launching of the Hubble Space Telescope, the community identified as one of the three "Key Projects" for it a definitive determination of the Hubble constant, to be achieved by studying Cepheid variables and other well-calibrated indicators in the Virgo cluster and slightly beyond. These then calibrate the Tully-Fisher relation, planetary nebulae, surface brightness fluctuations, and supernovae. The last set of observations will be gathered during HST Cycle 6 (currently in progress), the data reduced in 1997, and

archival papers published in 1998. It is widely believed that this will result in a definitive value of the Hubble constant, so that the rest of us can go home. Although I am enormously impressed by the papers so far published by the Key Project team, and have freely cribbed from them (Kennicutt et al. 1995, Freedman and Madore 1996, etc.), I am not a part of the "high optimism" wing of the astronomical distribution on this topic. More extended reviews of the history (Trimble 1996a) and current status of Hubble constant measurements (Trimble 1996b) will appear elsewhere.

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Table 1
Recently-published determinations of H

Year of Publication	Method	Value
Sept. 1992 to Sept. 1993	Median of 12 papers	75
Late 1993	Sunyaev-Zeldovich effect in Abell 2218	20-75
	Planetary nebulae in Fornax cluster	75 ± 8
	Hubble diagram of SNe Ia	47 ± 7
	12 clusters, many calibrators	87.3 ± 1.1
	Specific frequencies of globular clusters in Es	85
1994	Sunyaev-Zeldovich effect in Abell 2218	65 ± 25
	Brightest stars	71
	Velocities toward & away from Virgo; infall	84 ± 2.4
	Models of SN Ia light curves	66 ± 10
	Supernovae and Tully-Fisher	86 ± 7
	SN 1937A and new comparison star data	50, +6, -12
	SN 1937A + Cepheids in IC 4182	52 ± 9
	Tully-Fisher with Malmquist correction	48 ± 5
	SN 1992am (Type II), expanding photosphere method	81, +17, -15
	Expanding photosphere method for SN Iis	$73 \pm 6 \pm 7$
	Infrared Tully-Fisher toward Coma	77 ± 5
	SNe Ia in NGC 5253 + Cepheids	44-63
	Virgo Cepheids	87 ± 8
	Key Project - Virgo Cepheids as calibrators	80 ± 17
	Gravitational lensing data + model	≤ 70
	Many calibrators for many clusters	≥ 75
1995	Type Ia supernovae	52 ± 10
	Type Ia supernovae	60 ± 8
	Type Ia supernovae	80
	Scale lengths of spiral galaxy disks	93
	Specific frequencies of globular clusters	55 ± 7
	Type Ia supernovae	51 ± 7
	Type Ia supernovae	60
	Globular cluster luminosity function	80
	Type Ia supernovae	60, +14, -4
	Decaying neutrinos as dark matter	54
	Sunyaev-Zeldovich effect	75, +30, -21
	Type Ia supernovae	50, +30, -20
	Key project	80 ± 17
	Giant Elliptical Galaxies	69 ± 8
	Tully-Fisher relation	50 ± 5
	Type Ia supernovae	≤ 63
	Key project	80 ± 17
	Type Ia supernovae	55-60
	Globular clusters	64 ± 12
	Type I supernovae	76 ± 6
1996 (to early March)	Gravitational lensing	≤ 70
	Surface brightness fluctuations	55, +8, -4
	Luminosity function of planetary nebulae	84 ± 4
	Stability of S gas disks (new "ratio" method)	76 ± 8
	Type Ia supernovae	66 ± 10