Updating the Original Hubble Law

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ABSTRACT

Hubble (1929) presented the first clear relationship between the redshift of a galaxy and its distance, a relationship that would later bear his name as the "Hubble Law." This initial work used twenty-four nearby galaxies and found a Hubble constant of 500 km/s/Mpc. I have used modern values for the redshifts and distances to these galaxies to update the original Hubble Law. I determine the Hubble constant to have a value of 87 km/s/Mpc, and a preferred value of 68 km/s/Mpc when restricting the sample to only those objects with consistently calibrated Cepheid distances. The velocities have not changed significantly from Hubble's era, but the distance estimates to galaxies have increased by roughly a factor of ten, and this has led to the change in the slope of the Hubble Law.

1. Introduction

In a National Academy of Sciences proceeding, Hubble (1929) first presented the linear relationship between the galaxies and redshifts, a relationship that would come to be known as "Hubble's Law." In the late 1920s, there only existed about 50 galaxies with measured redshifts, and for only about half of these could astronomers of the day estimate distances – typically by identifying the brightest stars (e.g., Cepheid variables) and comparing the apparent magnitude to each type's calibrated absolute magnitude. Moreover, observed redshifts had to converted to heliocentric values to account for the solar motion, and this correction was still being refined in 1929.

The relationship Hubble found indicated a slope of 500 km/s/Mpc when plotting distances against redshifts. This slope is now known as the Hubble constant, or H_0. A value of 500 km/s/Mpc suggests a very a small, young universe (younger than the Earth, in fact) and is an order of magnitude larger than the best estimates made today (e.g., $H_0 = 72 \pm 8$ km/s/Mpc, Freedman et al. 2001).

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In order to investigate this discrepancy, I have used the NASA Extragalactic Database (NED[2]) to search for modern values of the heliocentric redshift and papers reporting measurements of the distances to the very same galaxies Hubble originally used. Below I describe the new data (§2), report my results for the Hubble constant (§3), discuss the result (§4), and draw my conclusions (§5).

2. Modern Data

NED is a great starting place to collect fundamental properties of extragalactic objects. The database ties together many sources of information spanning the entire electromagnetic spectrum, and includes images, photometry, redshifts, Galactic extinctions, and references. This is the place to go for a compilation of heliocentric velocities for pretty much any galaxy at all. This is also a good place to go initially for leads on distance measurements.

The most reliable direct distance indicators for distances out to the Virgo Cluster are Cepheid variable stars, which have a tight relationship between their period and luminosity. A NED reference list for one galaxy pointed at the Ferrarese et al. (2000) compilation of ground-based and space-based measurements of distances to galaxies based on Cepheids. A third of the 24 Hubble galaxies are present in this compilation. I realized that another object in the list, NGC 4258, had a more recent Cepheid distance recently obtained (Newman et al. 2001) to compare to a geometric distance measured from a nuclear maser disk.

For the remaining galaxies I had to look harder. I found a compilation of distances based on the technique of surface brightness fluctuations (SBF) by Tonry et al. (2001). Bottinelli et al. (1984) had a large compilation of Tully-Fisher distances and most of the remaining galaxies were included there, although I've been told the numbers from this paper are not very good (M. Pierce, private communication). I also had another Tully-Fisher distance from a paper comparing distances using that technique to those obtained using supernovae (Pierce 1994).

Table 1 gives the updated measurements for the 24 Hubble galaxies. Note that I've retained the order that Hubble used, which was in increasing order of distance (from 0.032 Mpc to 2.0 Mpc in his paper). It is clear from Table 1 that not only has the distance order changed, but that the range is much greater (from 0.05 Mpc to 16.8 Mpc).

[2]The NASA/IPAC Extragalactic Database (NED) is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

3. Results

Figure 1 shows the results. I have plotted (using supermongo) the galaxies with heliocentric velocities in km/s on the y-axis, and distances in Mpc on the x-axis, just as did Hubble. I've distinguished the more reliable Cepheid-derived distances with the filled circles. For a more important paper than a weekly homework assignment, I would have also plotted the error bars on each point, but Hubble did not estimate his errors and for the purposes of updating his result they are not that critical (although they certainly are critical to obtaining the best answer!).

In order to measure a slope, I used a statistical package called minitab to fit a regression line to the data. There are many methods to fit a line to data, some are better than others, and many software packages that implement these methods. A very good general software package called gaussfit is available as a contributed package inside IRAF; gaussfit is a robust, general, non-linear fitting program that allows any data set (with errors on every measurement) to be fit with any user-specified model.

I elected to use an ordinary least squares regression line (e.g., Bevington 1969) to fit the points in Figure 1. This type of fit assumes no error in one axis (I selected velocity) and all the error on the other axis (I selected distance). These errors could be explicitly included in the line fit, but I have assumed they are equal (which is approximately true for the majority of the points). Looking at Table 1, the relative uncertainty in distance is much larger than in velocity, although an inspection of velocities for a galaxy in NED shows that systematic errors can be much larger than the formal errors quoted.

When I fit the entire data set, and restricted the line to pass through the origin, I obtained the relationship:

$$Distance(Mpc) = (0.0115 \pm 0.0012) \times Velocity(km/s) \tag{1}$$

I get this result because I am finding the dependence of the uncertain variable distance on the better determined variable velocity. In order to get a slope for the quantities as plotted, and hence a measurement of the Hubble constant, I must take the reciprocal of the coefficient. I then obtain the result that $H_0 = 87$ km/s/Mpc, with a 1-σ range of 79 to 97 km/s/Mpc (these are formal fitting errors and do not include any systematic errors). The regression line with a slope of 87 km/s/Mpc is shown in Figure 1 as the dotted line.

I also decided to fit a line to only the points with Cepheid distances. I obtained:

$$Distance(Mpc) = (0.0155 \pm 0.0016) \times Velocity(km/s) \tag{2}$$

This result indicates that $H_0 = 68$ km/s/Mpc, with a 1-σ range of 58 to 83 km/s/Mpc. This line is is shown in Figure 1 as the solid line.

4. Discussion

A comparison between Table 1 and Hubble's Table 1 shows that the velocities are very similar, but that the modern values for the distances are on order of ten times larger than Hubble's determination. Otherwise everything else appears similar, and both plots show similarly strong correlations. It is beyond the scope of this assignment to determine just how and why the distance calibration has changed over the last 70 years, but it is clear that it has. Hubble based distances for several of his galaxies upon Cepheid variables, just as we have, so it must be the distance scale calibration that has changed, in particular the Cepheid calibration. There will be more this semester in ASTR 5440 and 5460 on the cosmological distance ladder and discussion about how each rung depends on the one beneath it. For external galaxies, the bottom rungs are the Magellanic clouds and their exact distances are hotly debated.

Also noteworthy is the fact that there are negative velocities and a lot of scatter near the origin. This represents the phenomenon of *peculiar velocities*, or a component of motion that has to do with local effects and is not characteristic of the general expansion of the universe. These velocities diminish relative to the Hubble velocities at larger distances. The peculiar velocities are not simply complications in measuring the Hubble constant, but are worth studying in their own right and place their own constraints on cosmological models.

5. Conclusions

Using modern data for the distances to the original Hubble galaxies results in a modern value of the Hubble constant (e.g., 68 km/s/Mpc using only Cepheid distances). The distance ladder calibrations have changed over the past 70 years.

This research has made use of the NASA/IPAC Extragalactic Database (NED) which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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Table 1. Modern Velocities and Distances to the Hubble Galaxies

Name (1)	Velocity (2)	$m - M$ (3)	Distance (4)	Reference (5)
SMC	158±4	18.99±0.05	0.063	1
LMC	278±2	18.50±0.13	0.050	1
N6822	-57±2	23.49±0.09	0.499	1
N598	-179±3	24.64±0.09	0.847	1
N221	-205±8	24.55±0.08	0.813	2
N224	-300±4	24.44±0.1	0.773	1
N5457	241±2	29.34±0.1	7.38	1
N4736	308±1	28.58±0.18	5.20	2
N5194	463±3	29.42±0.27	7.66	2
N4449	207±4	27.88±0.5	3.77	3
N4214	291±3	27.6±0.5	3.31	4
N3031	-34±4	27.96±0.26	3.91	2
N3627	727±3	30.06±0.17	10.28	1
N4826	408±4	27.09±0.18	2.62	2
N5236	516±4	28.36±0.46	4.70	3
N1068	1137±3	29.56±0.30	8.17	3
N5055	504±4	29.11±0.16	6.64	3
N7331	816±1	30.89±0.10	15.07	1
N4258	448±3	29.4±0.09	7.59	5
N4151	995±3	28.39±0.25	4.76	3
N4382	760±12	29.59±0.09	8.28	2
N4472	868±8	31.06±0.10	16.29	2
N4486	1282±9	29.72±0.14	8.79	2
N4649	1413±10	31.80±0.09	16.83	1

Note. — Col. (1): Galaxy designations from the NGC, in the same order as presented by Hubble (1929). Col. (2): Heliocentric redshifts in (km/s) taken from RC3 (ref. 1) or NED.
Col. (3): Distance modulus from the references (col. 5).
Col. (4): Distances in Mpc claculated from col. 3.
Col. (5): Distance references. 1. Ferrarese et al. 2000. 2. Tonry et al. 2001. 3. Bottinelli et al. 1984. 4. Pierce 1994. 5. Newman et al. 2001.

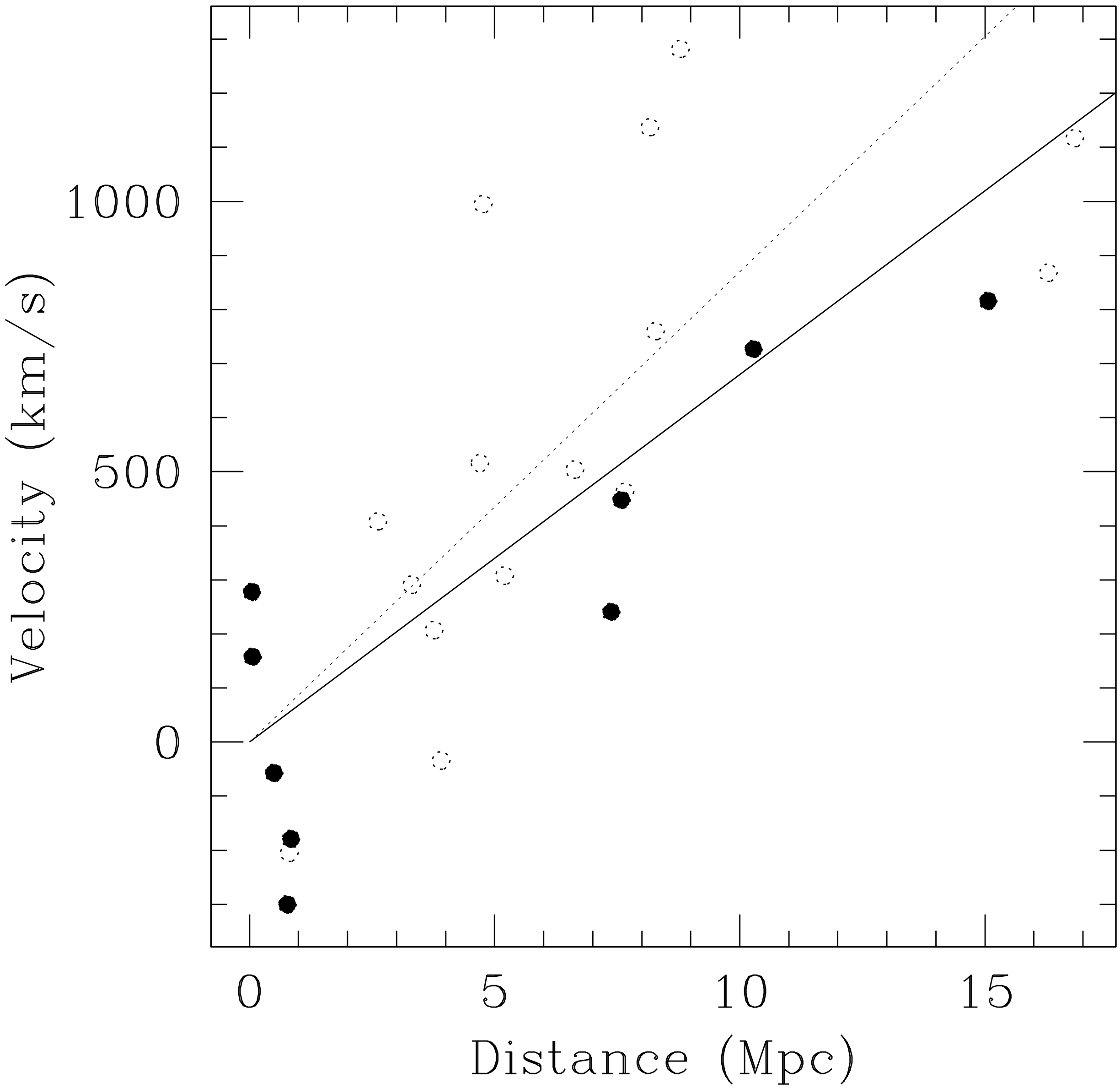

Fig. 1.— The updated Hubble Law, using modern values for the heliocentric velocities and the distances. Filled circles represent galaxies with Cepheid distances, while open circles represent galaxies with distances obtained with other techniques. The solid line represents a fit to the filled circles only, while the dotted line represents the best-fit line to the entire sample.