Hubble's Law and Hubble Constant

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Introduction

Hubble's Law relates the distance and velocity of receding galaxies using a constant known as the Hubble Constant. This lab activity calculated the Hubble Constant and approximated the age of the universe using publicly available data, using Edwin Hubble's original principles.[1]

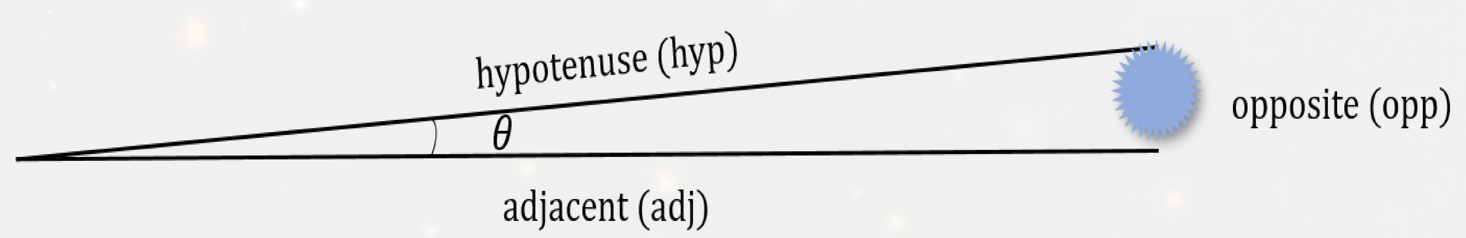
Theory

The Hubble Law relates a galaxy's velocity v with its distance d and the Hubble Constant H_0. This makes the Hubble Constant the slope of the graph of distance plotted against velocity.

$$v = H_0 d$$

To determine the Hubble Constant, "standard candles" such as a type of galaxy, supernova, or other event with well-understood size and magnitude is used. This study used galaxies approximated to be 22 kiloparsecs across.

Assuming galaxies of size 22 kiloparsecs (1 kpc = 3.26×10^3 light years), trigonometry with the small angle approximation can be used to calculate distance of galaxies θ radians in angular size:



$$\sin\theta = \frac{opp}{hyp} \Rightarrow \theta = \frac{0.022\ \mathrm{Mpc}}{d}$$

Rearranging for distance d, this gives:

$$d = \frac{0.022\ \mathrm{Mpc}}{\theta\ \mathrm{milliradians}}$$

Velocity v can be determined by examining the redshift z of spectral lines—places on the light spectrum where common elements like hydrogen and calcium absorb or emit light. This gives v as a factor of the speed of light c:

$$v = zc, \text{ where}$$

$$z = \frac{\lambda_{measured} - \lambda_{true}}{\lambda_{true}}$$

where $\lambda_{measured}$ is the measured wavelength of some spectral line from a moving galaxy and λ_{true} is the stationary, lab-determined value for that spectral line's wavelength.

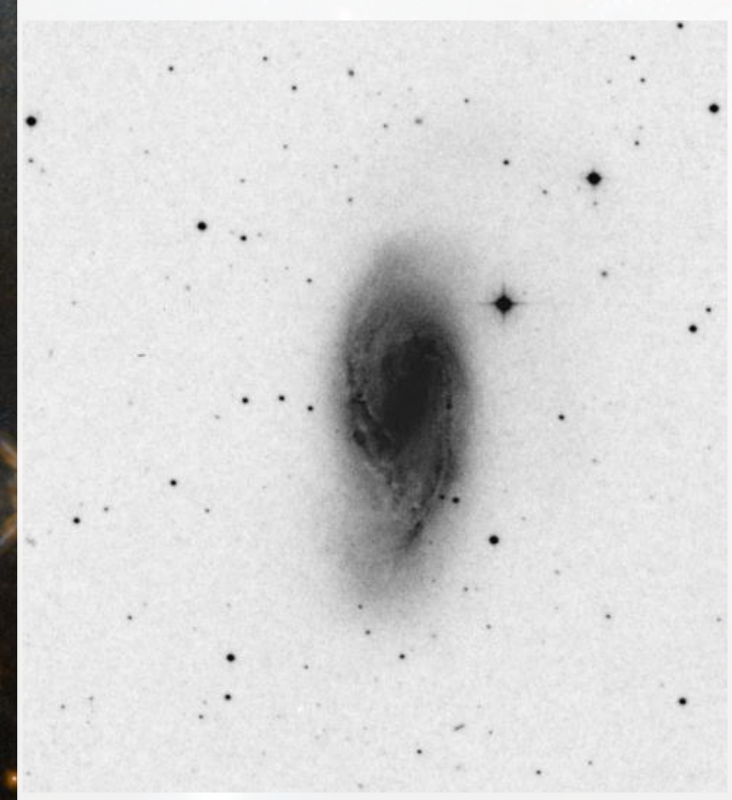
The age of the universe is inversely proportional to the Hubble Constant:

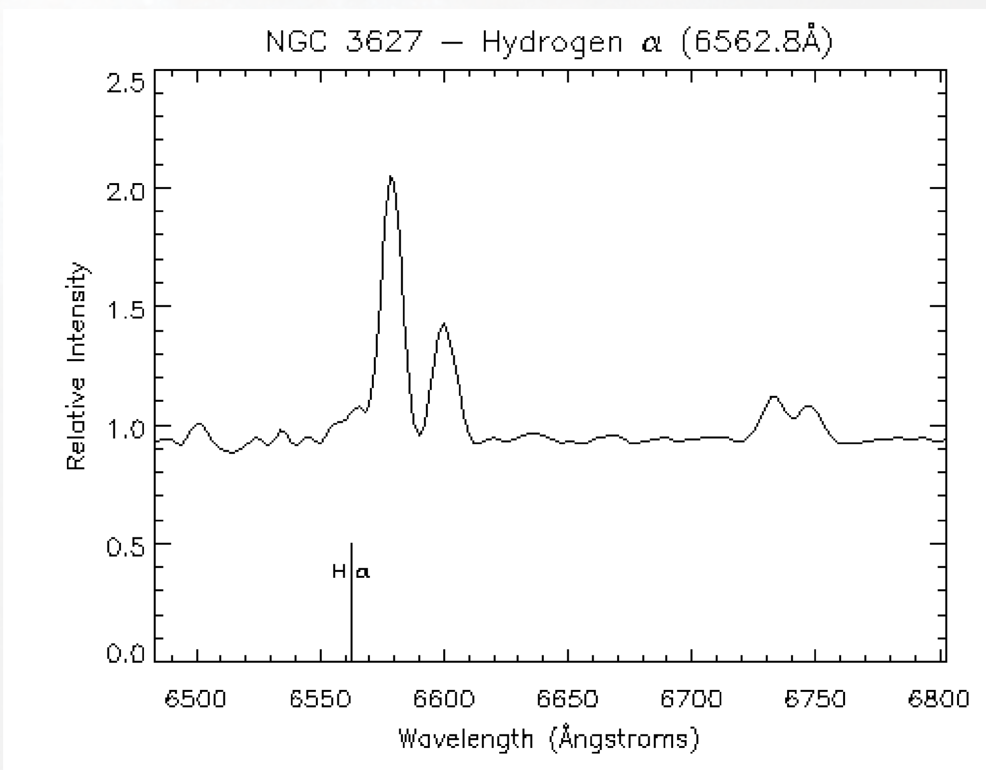
Theory, cont.

$$\frac{1}{H_0} \times 1000 = \text{age of universe in billions of years}$$

Methodology

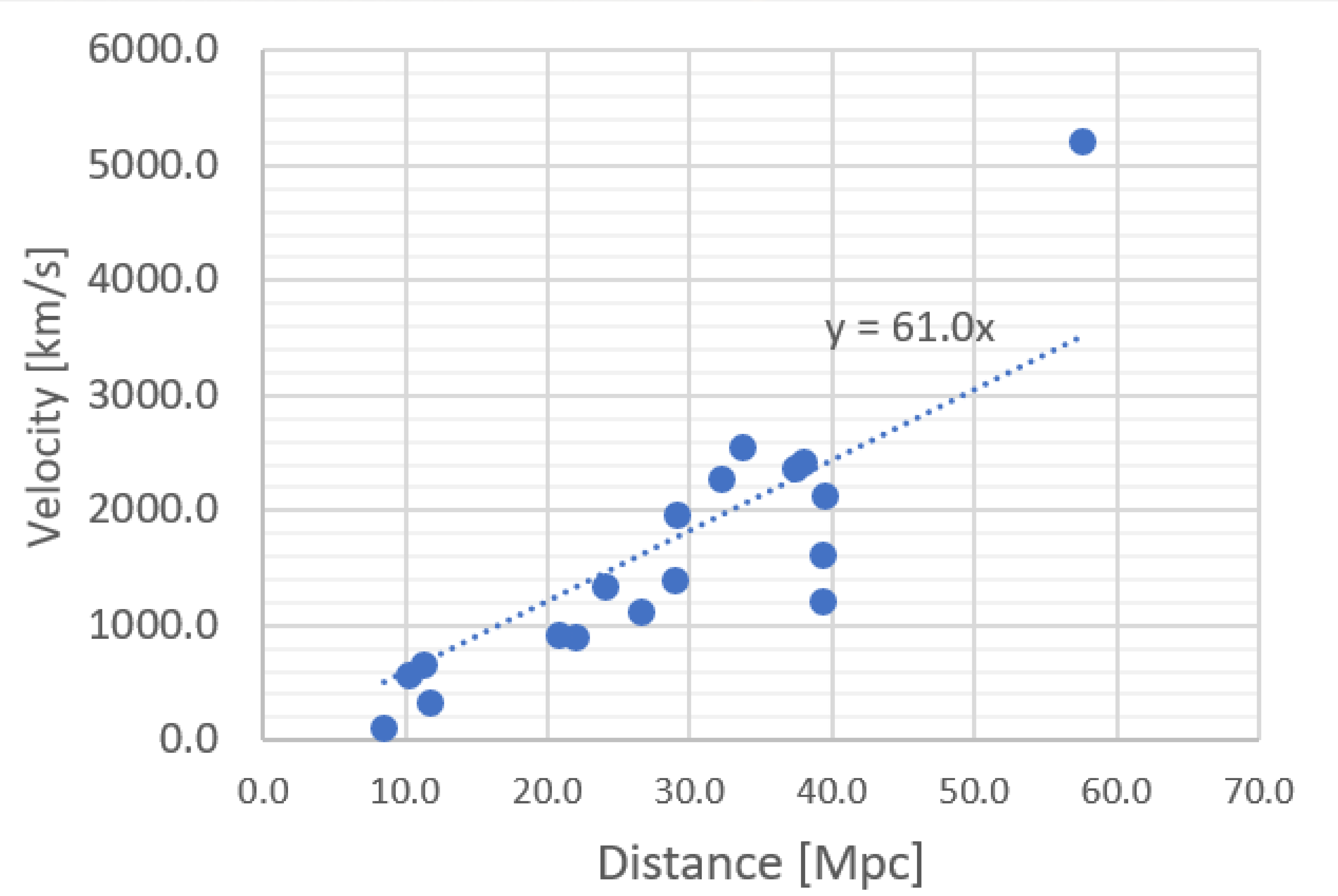
Galaxy images were evaluated for angular size and light spectrographs analyzed for the shifted wavelengths of three spectral lines, Ca_{II} H and Ca_{II} K (calcium) absorption lines and H_α (hydrogen) emission lines. Visual point-and-click analysis tools were built into the webpage, provided by the University of Washington's Astronomy Education Department. The galaxy was measured along the long edge, and the wavelength values taken for the appropriate peaks on the spectrographs. Below is a sample of the images analyzed for galaxy NGC 3627.





Results

Galaxy Velocity vs. Distance



Results, cont.

Hubble Constant H_0 was found to be 61.0 ± 4.7 km·s^{-1}·Mpc^{-1} (kilometers per second-megaparsec), with a universe 16.4 ± 1.3 billion years old. Uncertainty was calculated in Excel by the least-count-squares method.

Discussion and Conclusion

Results are consistent with the currently understood range of the Hubble Constant[2] (upper 60s to lower 70s of km·s^{-1}·Mpc^{-1}). The estimate for the age of the universe is reasonable, as the oldest stars known are 12.5 billion years old.

Additional systematic error may be present due to the analysis method, which involved the observer clicking on the edges of each galaxy. As the galaxies have no hard edge, this necessitates interpretation. Galaxies may also not all be 22 kpc across.

Note that a high degree of variability exists in modern determinations of the Hubble Constant using different standard candles and methodologies.

Despite the limitations of this study, this mirrors the theoretical methodology of Edwin Hubble. His discovery of an expanding universe helped affirm Einstein's theory of general relativity and drastically changed cosmology by disproving the widely-held notion that the universe was static.

Sources and Acknowledgements

[1]Neta A. Bahcall, PNAS, 11, 112 (2015);
doi: 10.1073/pnas.1424299112
[2]NASA, "Hubble Constant, H_0," LAMDA Education,
https://lambda.gsfc.nasa.gov/education/graphic_history/hubb_const.cfm.

Data sourced from the University of Washington at https://depts.washington.edu/astroed/HubbleLaw/galaxies.html

I would like to thank the University of Washington for providing data publicly for students such as myself to use, and Longwood University for helping facilitate this lab.

Background: Hubble/ESA