University of Science and Technology at Zewail City

Report VII

Observational Astrophysics Laboratory (PEU-327)

Lab VII

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Contents

Experiment (XIII):
Using Cepheid Variable Stars to Determine the Distance to Messier 100 Spiral Galaxy and Estimate the Age of the Universe

1.1 Task I: Calculating M for Cepheid stars

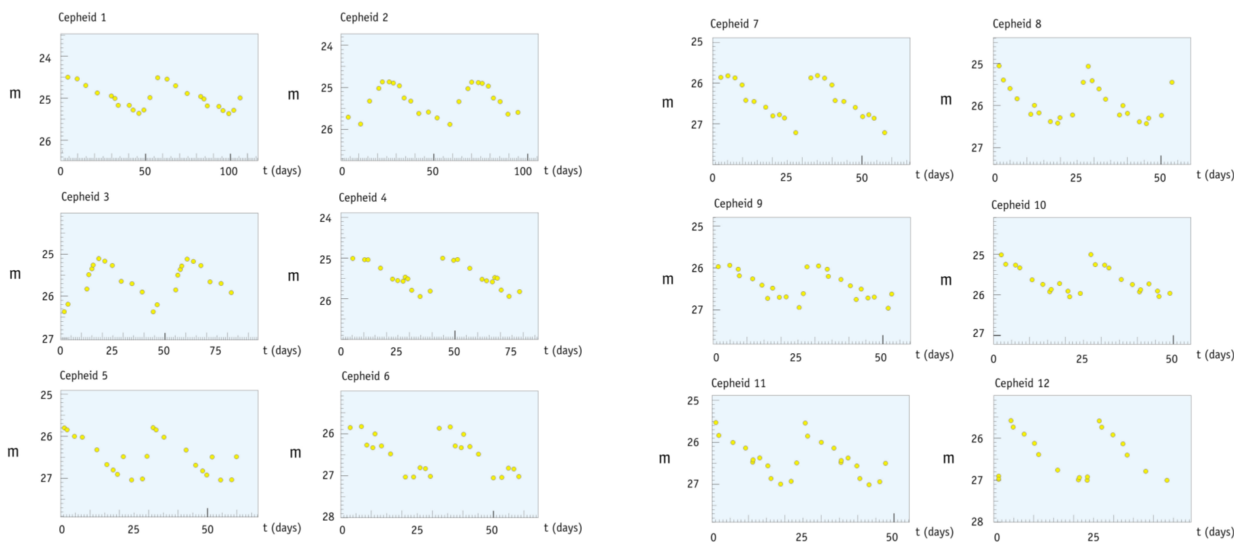

Figure 1: Cepheid Light Curves

$\because$ M = -2.78 $\log(P) - 1.35$

Table 1: Properties of Cepheid Variables

Cepheid	Period (P, days)	Magnitude (M)
1	60	-6.29
2	50	-6.07
3	40	-5.8
4	40	-5.8
5	30	-5.45
6	25	-5.23
7	28	-5.37
8	28	-5.37
9	28	-5.37
10	28	-5.37
11	26	-5.28
12	26	-5.28

1.2 Task II: calculating m and d

$$\langle m \rangle = \frac{m_{\min} + m_{\max}}{2}$$

$$d = 10^{\frac{m-M+5}{5}}$$

Cepheid	m_{min}	m_{max}	$\langle m \rangle$	**d (Mpc)**
1	25.5	24.5	25	18.11
2	25.9	25.2	25.6	21.57
3	26.4	25.1	25.8	20.89
4	26	25	25.5	18.19
5	27.1	25.8	26.45	23.98
6	27	26.2	26.6	23.22
7	27.2	26.2	26.7	25.94
8	26.5	25.1	25.8	17.14
9	27	26	26.5	18.79
10	26.1	25	25.6	15.63
11	27	25.5	26.3	20.7
12	27	25.6	26.3	20.7

Table 2: Properties of Cepheid Variables

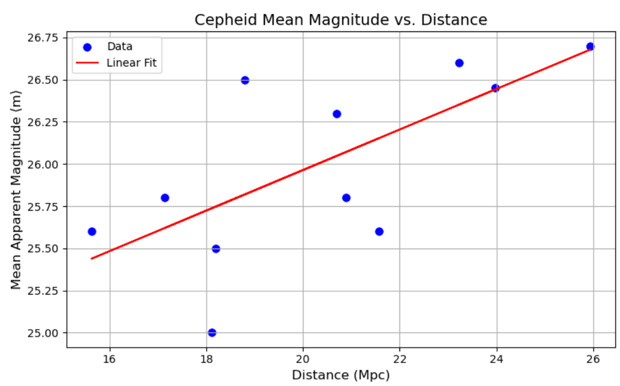

Figure 2: Regression Plot: Mean Magnitude vs Distance

1.3 Task III: Discussion about the distances

Different factors can affect the calculation of distances to Cepheids:

- Different Cepheids have different light curve amplitudes and shapes, which can cause variations in apparent brightness and make it difficult to precisely calculate their distances based only on light curves.
- Assuming no absorption or reddening by interstellar dust.
- Sampling limitations in datacurves.
- Noise in observations.

[1]The $\langle m \rangle$ formula was found to be most suitable [1].

1.4 Task IV: Impact of the spatial positions of stars on distances

- Distance estimates from the twelve Cepheids in M100 vary due to observational and intrinsic factors.
- Cepheids serve as standard candles via the period-luminosity relation; averaging their distances provides an estimate for M100.
- The variation is not primarily due to their spatial distribution in M100.
- For context:
  - The Milky Way spans ∼0.03 Mpc [5]; assuming M100 is similar.
  - This is negligible compared to the observed spread of ∼10 Mpc.
- Dominant sources of variation include:
  - Photometric and measurement uncertainties.
  - Dust extinction.
  - Intrinsic scatter in the period-luminosity relation.

1.5 Task V: Estimating the Distance to M100

- The mean distance to the twelve Cepheid variables is calculated as:

$$\langle D \rangle = \frac{1}{12} \sum_{i=1}^{12} D_i \approx 20.29 \ \ \text{Mpc.}$$

- The original Hubble paper reports a distance to M100 of 17.1 ± 1.8 Mpc [3].
- The calculated value is slightly higher, likely due to uncorrected extinction, photometric uncertainties, or systematic differences in data processing.
- Despite the discrepancy, the result is within a reasonable range, demonstrating the utility of Cepheid variables as standard candles.
- The relative error is computed as:

$$\text{Relative Error} = \frac{|\langle D \rangle - D_{\text{ref}}|}{D_{\text{ref}}} = \frac{|20.29 - 17.1|}{17.1} \approx 18.7\%$$

1.6 Task VI: Estimating Hubble's Constant

- Hubble's law relates the recessional velocity v of a galaxy to its distance D via:

$$H_0 = \frac{v}{D}$$

- Given [2]:

$$v = 1400 \text{ km/s}, \quad \langle D \rangle = 20.29 \text{ Mpc}$$

$$\therefore H_0 \approx 69.0 \ \frac{\text{km}}{\text{s Mpc}}$$

1.7 Task VII: Estimating the Age of the Universe

- The age of the Universe can be approximated by the inverse of the Hubble constant:

$$t_0 = \frac{1}{H_0}$$

- Given:

$$H_0 = 69.0 \ \frac{\text{km}}{\text{s Mpc}}$$

- Convert H_0 to SI units:

$$H_0 = 69.0 \ \frac{\text{km}}{\text{s} \cdot \text{Mpc}} = 69.0 \ \frac{10^3 \ \text{m}}{\text{s} \cdot 3.086 \times 10^{22} \ \text{m}} \approx 2.236 \times 10^{-18} \ \text{s}^{-1}$$

- Therefore, the estimated age of the Universe is:

$$t_0 = \frac{1}{2.236 \times 10^{-18} \ \text{s}^{-1}} \approx 4.47 \times 10^{17} \ \text{s} \approx 14.2 \ \text{billion years}$$

- The Earth is approximately 4.54 billion years old.
- Thus, the Universe is about:

$$14.2 - 4.54 = 9.66 \ \text{billion years older than the Earth.}$$

- The relative error is computed as:
  - Given [4]:

$$\because t_0^{\text{ref}} = 13.6 \ \text{billion years} \qquad \because t_0 = 14.2 \ \text{billion years}$$

  - The relative error is given by:

$$\text{Relative Error} = \frac{|t_0 - t_0^{\text{ref}}|}{t_0^{\text{ref}}} \times 100\%$$

$$= \frac{|14.2 - 13.6|}{13.6} \times 100\% \approx 4.41\%$$

  - Therefore, our estimate differs from the reference by approximately **4.41%**.

Experiment (XIV)
Reproducing Hubble's Law and Examining Quazar's Emision

2.1 Task 0: Preliminary Questions:

- $\Delta\lambda = \lambda_{\text{moving}} - \lambda_{\text{rest}}$ where, $\lambda_{\text{moving}} \equiv$ The measured wavelength in the moving frame, and $\lambda_{\text{rest}} \equiv$ The measured wavelength in the rest frame. Thus, Z becomes,

$$Z = \frac{\lambda_{\text{moving}} - \lambda_{\text{rest}}}{\lambda_{\text{rest}}}$$

- smaller.
- since v is a positive quantity, therefore, **faster**. (moving away from us).
- $Mpc = 3261564\, ly \approx 3.26 \times 10^6 ly$

2.2 Task I: Determine the Apparent Size and Distance:

Table 3: Galaxy Properties

Galaxy	θ **(as)**	**D (Mpc)**
NGC 3434	120	50
NGC 4911	33	181.82
NGC 5584	170	35.29
COSMOS 3127341	7	857.14
Arp 148	25	240

2.3 Task II: Determine the Redshift and the Recession Velocity:

Galaxy	$\lambda^{H\beta}_{\text{galaxy}}$	$\lambda^{H\beta}$	$\Delta\lambda^{H\beta}$	$z_{H\beta}$	$\lambda^{H\alpha}_{\text{galaxy}}$	$\lambda^{H\alpha}$	$\Delta\lambda^{H\alpha}$	$z_{H\alpha}$	z_{avg}	v (m/s)
NGC 3434	486.1	492.1	6.0	0.0122	656.2	664.5	8.3	0.0125	0.01235	3.705×10^6
NGC 4911	486.1	500.0	13.9	0.0278	656.2	675.0	18.8	0.0279	0.02783	8.35×10^6
NGC 5584	486.1	488.8	2.7	0.00524	656.2	660.0	3.8	0.00576	0.0055	1.65×10^6
COSMOS 3127341	486.1	545.0	58.9	0.1081	656.2	735.0	78.8	0.1072	0.10765	32.30×10^6
Arp 148	486.1	503.5	17.4	0.03456	656.2	679.5	23.3	0.03429	0.034425	10.328×10^6

Table 4: Galaxy data including observed and emitted wavelengths for Hβ and Hα lines, redshifts, and radial velocities.

2.4 Task III: Hubble Plot:

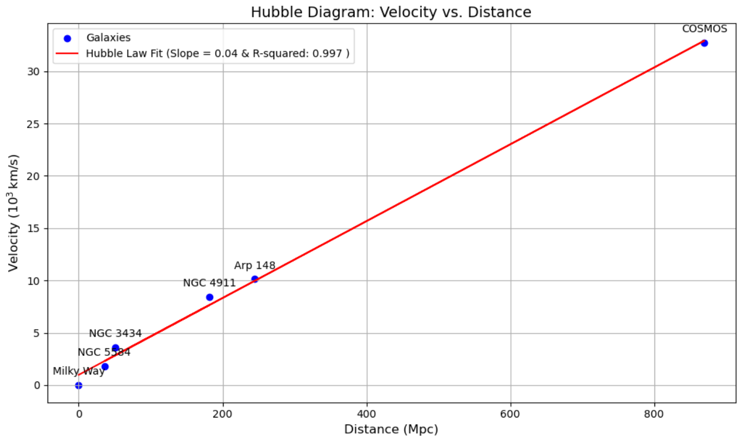

Figure 3: Regression Hubble Plot: velocity vs Distance

2.5 Task IV: Determine the Hubble Constant and the Age of the Universe:

- Given:

$$H_0 = 0.03672 \times 1000 \ \frac{\text{km}}{\text{s Mpc}} = 36.72 \ \frac{\text{km}}{\text{s Mpc}}.$$

- Taking the speed of light,

$$\begin{aligned} D &= \frac{c}{H_0} \\ &= \frac{3 \times 10^8 \, \frac{\text{km}}{\text{s}}}{36.72 \, \frac{\text{km}}{\text{s Mpc}}} \\ &= 8.16993 \times 10^3 \, \text{Mpc} \\ &= 2.66467 \times 10^{10} \, \text{ly} \\ &= 26.6467 \, \text{billion ly.} \end{aligned}$$

$\therefore$ Using this analysis the Big Bang happened 26.65 billion years ago which is completely double the real value [4].

2.6 Task V: Apply Hubble's Law to a Quasar:

2.6.1 Determining the diameter

Galaxy	$\lambda^{H\beta}_{\text{galaxy}}$	$\lambda^{H\beta}$	$\Delta\lambda^{H\beta}$	$z_{H\beta}$	$\lambda^{H\alpha}_{\text{galaxy}}$	$\lambda^{H\alpha}$	$\Delta\lambda^{H\alpha}$	$z_{H\alpha}$	z_{avg}	v (m/s)
3C 273	486.1	563	76.9	0.1366	758	101.8	101.8	0.1343	0.13545	40.634×10^6

Table 5: Properties of Galaxy 3C 273

Galaxy	θ **(as)**	**D (Mpc)**	d_H **(pc)**	d **(kpc)**
3C 273	20	300	1.11×10^3	111

2.6.2 Calculation of the absolute brightness

$$\therefore d_{ly} = 3.6186 \times 10^8 ly$$

$$\because m - M = 5\log(d) - 5 = 37.7927^{\text{mg}}$$

$$\therefore M = 13 - 37.7927 = -24.7927^{\text{mg}}$$

2.6.3 Calculation of the energy output of the quasar

The Sun's absolute magnitude is $M_\odot = 4.8^{\text{mg}}$, while the quasar's is:

$$M_{\text{quasar}} = -24.7927^{\text{mg}}$$

The brightness difference:

$$\Delta M = 29.5927^{\text{mg}}, \quad \text{so} \quad \frac{L_{\text{quasar}}}{L_\odot} = 10^{\Delta M/2.5} \approx 9.1 \times 10^{11}$$

Assuming 1% energy efficiency for both, and knowing the Sun consumes 1 $M_\odot$ over 10^{10} years, the quasar's fuel rate is:

$$\dot{M}_{\text{quasar}} = 9.1 \times 10^{11} \times 10^{-10} = 91\ M_\odot/\text{yr}$$

Discussion: Quasars are extremely luminous but compact, powered by matter falling into a supermassive black hole *(from PHYS 331)*. Due to their intense radiation, even a few light-years would be too close to safely approach.

References

[1] Philipp Engelmann. "Cepheid Stars as standard candles for distance measurements". In: (Sept. 2013). DOI: `https://www.haus-der-astronomie.de/3440685/04Engelmann.pdf`.

[2] W. L. Freedman et al. "Distance to the Virgo cluster galaxy M100 from Hubble Space Telescope observations of Cepheids". In: *Nature* 371.6500 (Oct. 1994), pp. 757–762. DOI: `https://doi.org/10.1038/371757a0`.

[3] W. L. Freedman et al. "Final Results from the Hubble Space Telescope Key Project to Measure the Hubble Constant". In: *The Astrophysical Journal* 553.1 (May 2001), pp. 47–72. DOI: `https://doi.org/10.1086/320638`.

[4] Rushikesh Lokhande. *Estimating the Age of the Universe: A Hubble Constant Approach*. Nov. 2023. DOI: `10.13140/RG.2.2.36292.03209`.

[5] NASA. *The Cosmic Distance Scale*. `https://imagine.gsfc.nasa.gov/features/cosmic/milkyway_info.html`. Accessed: 2023-10-XX. 2018.