Cepheid Variables

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This experiment was performed in collaboration with *Matthew Foale*.

Abstract

A distance to the NGC 4258 galaxy was determined by looking at Hubble Space Telescope (HTS) observations of twelve Cepheid variable stars in the outer parts of the galaxy. This was achieved by constructing light curves and determining the luminosity of stars. Comparing absolute and observed magnitudes allowed to determine the distance to each Cepheid and averaged out gave a value of the distance to the galaxy, which was found to be 8.2 ± 0.3 Mpc.

1. Introduction

Galaxy NGC 4258, also known as Messier 106, is a spiral galaxy like the Milky Way. However, it is unusual due to the two extra arms that are not aligned with the main disk. This phenomenon is caused by the supermassive black hole in the galaxy's centre, ejecting high-speed particles, which produce shock waves when colliding with a matter in the galactic plane. Consequently, some matter is pushed away from the main disk and heated up, produces radiation of different frequencies. The reduction of the matter in the main disk of the galaxy affects the usual star formation and the fate of the NGC 4258 [1]. For this experiment, we observed Cepheid stars on the outer edge of Messier 106.

Cepheid variables are named by a star called Delta Cephei - one of the first stars discovered in 1784, which showed a consistent fluctuation in their size and brightness. Type I Cepheids are yellow supergiants and occupy the instability strip in the Hertzsprung-Russel diagram, shown in Figure 1. They are up to 20 times more massive [2] and up to 50000 brighter than the Sun [3]. However, one of their most distinguishing features is the relationship between their brightness period and the absolute luminosity, with the period ranging from about 1 to 100 days [4]. Together with them being very bright, this fact makes Cepheids a perfect candidate for standard candles – a tool to measure intergalactic distances. The significance of this distance determination lies in calculating the Hubble's constant, which is related to the size and the rate of expansion of the universe [5]. This report is focusing on the estimation of the distance to the NGC 4258 using Type I Cepheids.

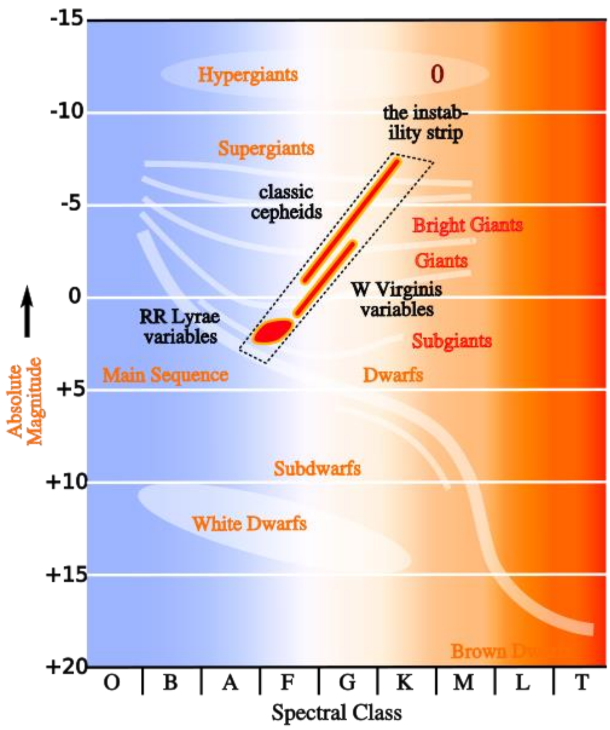

Figure 1. The Hertzsprung-Russel diagram, showing the absolute magnitude of different stars against their Spectral class (temperature scale). The instability strip is located by the dotted line. Type I Cepheids are located in the upper part of the denoted region [6].

2. Theory

Variable stars pulsate due to the ionisation and deionisation of the helium in their outer layer. Singly ionised helium He^{+1} is more transparent than the doubly ionised helium He^{+2}, which requires a hotter environment. When there is a lot of He^{+2} in the star's outer layer, less radiation can escape, and the star appears dimmer. Because of the extra radiation energy inside of the star, it heats up and pressure increases causing the star to expand. As the star expands, it cools down, so some of the He^{+2} atoms become He^{+1} by deionisation as they get one electron from the plasma [6]. The outer layer becomes more transparent, and more radiation escapes. At this period, a peak it the observed brightness can be seen. Escaping radiation causes the star to cool down even more, and the star collapses under gravity as it is no longer supported by the radiation pressure [7]. This shrinking increases the temperature and pressure, so the cycle repeats again. Both phases of this variation are shown in Figure 2.

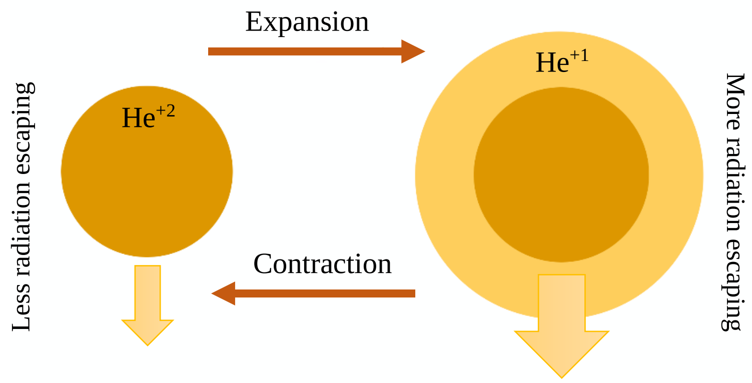

Figure 2. Two phases of the pulsating Cepheid star. The left picture shows the phase when the Cepheid appears dimmer because doubly ionised helium is blocking radiation. The right one shows the phase when the star appears brighter because singly ionised helium in the outer layer is more transparent to the radiation.

It was discovered that more luminous variable stars have longer periods. In fact, the luminosity is directly proportional to the period of brightness variation. The period luminosity relation of the Type I Cepheids for a light in an optical part of the spectrum is given by

$$M = (-2.43 \pm 0.12) \times (\log(P) - 1) - (4.05 \pm 0.02),$$

where M is the absolute magnitude of the star, and P is the period in days. Constants are determined empirically and have uncertainties associated with them [8]. Using this equation, the luminosity or the absolute magnitude of the observed Cepheid can be determined from its period of brightness variation.

The actual brightness of the star can be compared to the apparent brightness to determine the distance between the observer and the star r, which is the aim of this experiment. This is done using the distance modulus equation

$$m - M = -5 + 5\, log_{10}(r),$$

where m and M are the apparent and the absolute uncertainties, respectively [9].

3. Experimental approach

We used HST pictures and analysed them in the DS9 software to obtain the brightness of stars at different times of observation. HTS uses couple charged devices (CCDs), so the star's brightness was presented in terms of counts caused by radiation-induced charge in the semiconductor material of the chips via the photoelectric effect. In order to obtain counts of the actual star, background radiation had to be eliminated. This was done by considering two regions around the star, as shown in Figure 3.

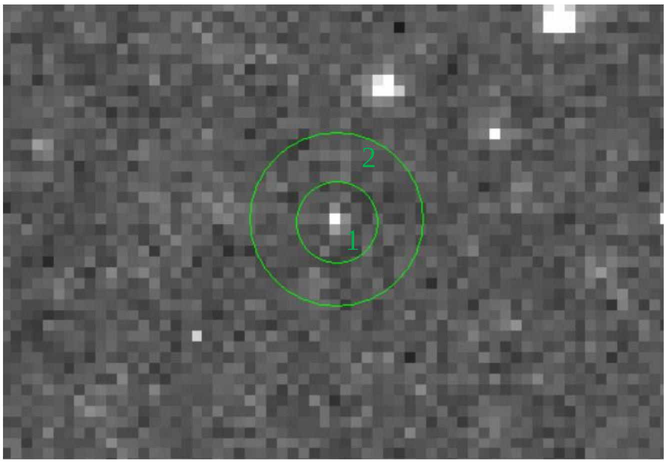

Figure 3. Showing two regions over which counts were obtained for a typical measurement. Region 1 is closer to the edge of the star to enclose all the radiation. Region 2 is wider to include some background, but with no other stars inside apart from the observed one.

A number of actual counts from the star c, without an influence of the background noise, was calculated using

$$c = c_1 - \frac{c_2 - c_1}{A_2 - A_1} \times A_1,$$

where c_1 and c_2 are total counts obtained in regions 1 and 2. A_1 and A_2 are the respective areas of these regions in pixels. Since each photon had the same probability of being detected and counts were independent of each other, a number of counts was assumed to follow the Poisson distribution. This meant that the uncertainty on the number of counts was given by the square root of the number of counts. Uncertainties for c_1 and c_2 were propagated to get the uncertainty on c.

Counts against the start of the exposure time were plotted to get a light curve. However, data points were distributed loosely across about two periods, so a phase folding technique was applied to get a more accurate period. Phases for all data points were calculated using a guess period, estimated from the initial plot. Data points outside of the first phase were shifted by the whole number of phases, by which they were away from the first one. In that way, all periods were stacked on one another. For this experiment, cepheids were usually observed for no more than two periods. The procedure was carried for a range of trial periods. The shortest string method was used as the goodness of fit parameter. Data points are most strongly correlated, where the sum of the distances between the neighbouring points was minimised. We noted that several trial periods gave minimal values for the shortest string. Therefore, we plotted string length against trial periods, which enabled us to clearly see the range of periods for which this value was the smallest. The median value of this range was taken as a period estimate and half of the range as an uncertainty estimate. A phase folded plot over two periods obtained for one of the Cepheids is shown in Figure 4.

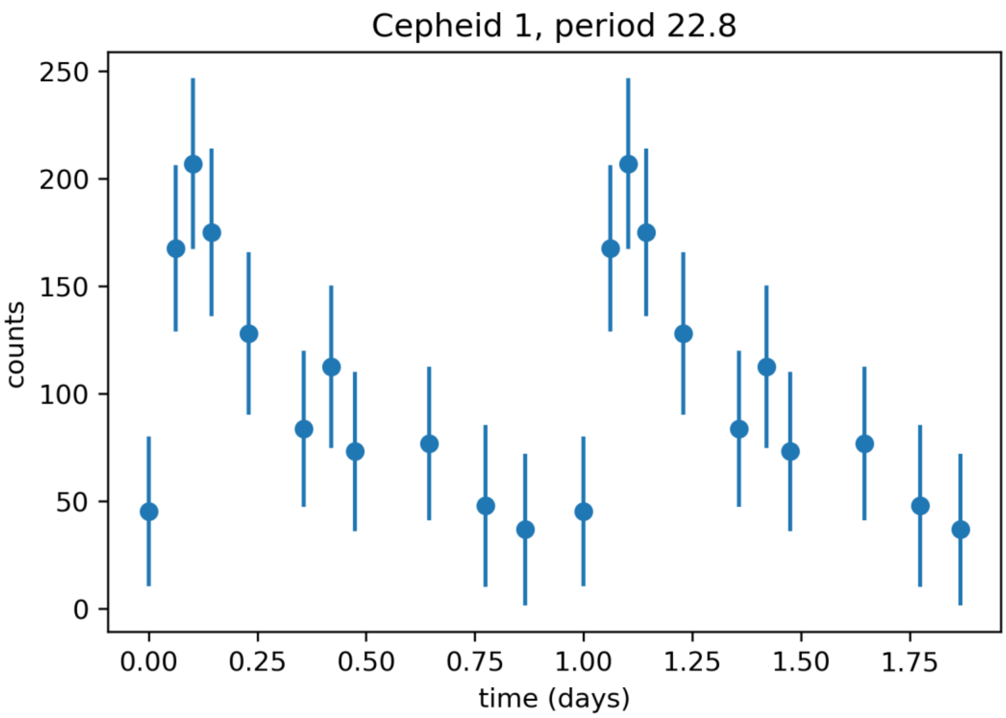

Figure 4. A phase folded light curve, showing the brightness variation over two periods of one of the examined Cepheids. The period at which phase folding was completed is 22.8 days.

The number of counts recorded by the HST is directly proportional to the number of incoming photons at a CCD's area, which is flux. Therefore, the apparent magnitude of the star m was determined using

$$m = m_0 - 2.5log_{10}\left(\frac{c}{c_0}\right),$$

where m_0 is the calibration magnitude when the number of counts is c_0 [9]. For CCD's used in this experiment, the calibration was m_0 = 22.57 for the c_0 = 1000 counts. The uncertainty of each calculated value of apparent magnitude was propagated from the uncertainty on counts. The weighted mean of all magnitudes for each star was used together with the determined period to find the distance to the Cepheid using period luminosity relation and distance modulus formulae, described in section 2.

4. Results

Calculated values of apparent magnitude, period, and distance for each measured Cepheid variable star is presented in Table 1.

Cepheid Number	Apparent Magnitude	Period/days	Distance/Mpc
1	24.7 ± 0.1	22.8 ± 0.8	8 ± 1
2	24.47 ± 0.08	17.3 ± 0.4	6.6 ± 0.9
3	24.7 ± 0.1	16.7 ± 0.2	7.1 ± 0.8
4	25.2 ± 0.1	15.5 ± 0.9	9 ± 2
5	25.4 ± 0.2	13.7 ± 0.5	9 ± 2
6	25.9 ± 0.3	19.0 ± 0.6	9 ± 1
7	24.8 ± 0.1	31.7 ± 0.6	10 ± 1
8	25.1 ± 0.1	26.1 ± 0.6	9 ± 1
9	24.8 ± 0.1	18.0 ± 0.3	10 ± 1
10	24.43 ± 0.09	16 ± 1	6 ± 2
11	25.1 ± 0.2	20.7 ± 0.9	7 ± 1
12	25.3 ± 0.2	24.0 ± 0.2	10 ± 1

Table 1. Apparent magnitude, the period of brightness variations and distance calculated using these values for each observed Cepheid with respective uncertainties.

A weighted mean of the calculated distances for all cepheids was used to calculate the final value for the distance to the NGC 4258 galaxy. This value was obtained to be 8.5 ± 0.3 Mpc. It is on the edge of being consistent with the previously known value of 7.576 ± 0.082 Mpc [5]. However, some of the previous work done regarding the distance to the NGC 4258 galaxy showed distances less than 7.5 Mpc, which is not consistent with our calculated result [10].

A few main sources of error affected the determined distance. A random error on counts contributed to the dominant error on period, which could be reduced by looking at more Cepheids and taking more measurements of the same stars by either making more frequent observations or observing stars for a longer time. The latter would be the most beneficial as more extended observations consist of a greater number of periods which is significant in using the phase folding technique. The most significant error, however, was the error due to the extinction of the galaxy. Dust inside the NGC 4258 and the Milky Way, as well as dust between them, scatters light of shorter wavelengths of the visible part of the spectrum, so observing a star in the visible light results it looking dimmer and redder than it actually is. This is a systematic error, which can be partially eliminated by looking at the infrared light emitted by the stars. However, the period luminosity relation is different for different parts of the electromagnetic spectrum, so it is not a simple correction.

5. Conclusions

The distance to the NGC 4258 was obtained to be 8.5 ± 0.3 Mpc by averaging distances to the several Cepheid variable stars on the edge of the galaxy exploiting their luminosity period relation for the optical part of the spectrum. The value is consistent with some of the previously obtained results of 7.576 ± 0.082 Mpc [5] but disagrees with others [10]. The main reason for this inconsistency is suggested to be laying in the extinction of the galaxy, which could be compensated by considering light of longer wavelengths emitted by the observed stars.

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