Astronomical Analysis on Star Exploration: A Quantitative Research on Luyten’s star based on Proper Motion and Photometric Brightness.

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Abstract. There are many intrinsic properties for the stars and some of them can be investigated by an astronomical way. Through an investigation on one Luyten’s star (LHS33), this paper presents one basic astronomical analysis method and result about its high proper motion, and brightness for four different filters (Rc, V, Blue, Ic). It is an essential element when exploring the target star and obtaining its properties. The method used in this study is a measurement of astrometric position and photometry. All of the measurements require the original CCD (Charge-coupled Device) images obtained from the telescope and a series of software processing. The results obtained mainly are about the value of proper motion, apparent magnitude in these 4 filters above. For instance, the proper motion calculated for right ascension (RA) is 0.59±0.10 arcsecs per year and for declination (Dec) is -3.70±0.11 arcsecs per year. The valued calculations suggest an agreement with current published data. It verifies the correction for both operation procedure and data analysis. It gives a specific interpretation on why such the observation happened based on the quantitative analysis.

1. Introduction

The universe has massive stars, and for every star, they have essential properties. One of the attractive star’s properties is proper motion. People are more inclined to investigate the minorities relatively rather than the general proportion. The same is true for astronomers to categorise the special proper motion such as the higher or lower values. In the last century, Luyten had been made a classification catalog such as Luyten Five-Tenths (LFT), Luyten Two-Tenths (LTT) and Luyten Half-Second (LHS) catalogue for gathering high proper motion stars [1]. And usually, the way of using proper motion is reasonable to find the nearby star. In recent years, many astronomers gradually made some improvements in the catalogs and brought us more accurate results. For instance, Samir with his colleagues integrate the results for both Two Micron All Sky Survey (2MASS) and the first Palomar Observatory Sky Survey (POSS I) to construct the precision and characterize the catalog [2]. Moreover, the “brightness” of the star can be another basic property which measured by astronomical photometry. The method can be used to study the variable star like the minor planet and supernovae even include its chemical composition by specific spectrophotometry [3]. So far, it has been formed a complete system that including collecting and sharing photometric data. Also, the establishment of some organizations like
the American Association of Variable Star Observers (AAVSO) suggested a reference for researchers [4].

In principle, it is essential to obtain the star’s astrometric position when calculating proper motion. In other words, the process of measurement on position becomes an inseparable part of proper motion. In addition, the data for “brightness” apart from proper motion is also needed. The brightness is one visualized property, whether with naked eyes or with tools when observing the target. That can be detected by photometric measurement based on the data obtained from the telescope. Also, we call the property to be the apparent magnitude. However, there are some critical issues like how to make use of the astrometric position and calculate the apparent magnitudes to achieve the corresponding properties analysis. And the problems about the connection of the data from CCD images and intrinsic stellar colours. The critical point is the converting from abstract and complex data to specific meaning quantities needed in a quantitative way, as shown in the paper.

The target star for this paper chosen is one of the Luyten’s star called LHS33, which is a low-mass red dwarf in the distance of 12.36 light-years from the Sun. Indeed, one of the features is its high proper motion. The proper motion can be considered angular motion in measuring the changed position of the star [5]. To investigate its properties, the element such as obtaining its astrometric and photometric measurement of LHS33 is considered necessary. Firstly, starting with an inspection of CCD images from a successive 5-year period. A series of CCD images contain the primary information like the star’s position such as right ascension (RA) and Declination (Dec), and the star signal corresponding the apparent magnitude of the star. Secondly, to calibrate the brightness of the Luyten’s star, some calibration reference stars in that field are used through four different filters (Rc, V, Blue, Ic) to obtain the calculated brightness through these filters. Thirdly, the comparison between the value calculated and published data was meaningful and allowed us to find consistency with those published data. In the end, the proper motion and related properties could be determined through the astronomical process.

2. Methods

2.1. Obtain position (RA&Dec).

All of the images obtained were from the C14 telescope based on the C14 Robotic Interface System (ChRIS). Each image contained all the information we needed, such as position. To ensure the position of each image has the same unified criteria, the ICRF/J2000.0 system was chosen to match the images. From images, we can obtain the (x, y) coordinate pixel directly, which means the pixel represents where it is in the sky. It is doable to determine the corresponding RA and Dec by the software tool GAIA. In other words, we can use GAIA to know the precise estimate of its position. The first thing is to estimate the image field of view or size. In the environment of GAIA, the cursor can read the value of alpha (RA) and sigma (Dec) so put the cursor to both the edge of images. Thus, the value of alpha and sigma obtained, then,

\[ \Delta \alpha (\text{dms}) = 15 \times \Delta \alpha (\text{hms}) \times \cos(\delta) \]  

(1)

To unified the different unit, here the arcsecond as the common unit is used. So based on the transform equation (1), we can achieve such the transform of RA and Dec.

2.2. Astrometric position measurements.

The exact position of the centroid of the target star and the calibration star C1 and C2 are obtained. Repeat this procedure for all the images in the 5 years period and record the corresponding RA and Dec.

2.3. Aperture Photometry.

The CCD images provide a mean of measuring star’s brightness and provide a value of star signal and sky signal(background). For this method, all stars are measured with an enclosed aperture of a certain size. The aperture is large enough to enclose most of the stellar images so the software (GAIA) can sum
all of the pixel signals within the aperture. To be accurate for the star signal, one way to calculate the star signal is to subtract the background signal from the total signal. Next, putting three apertures on the LHS33, C1 and C2 respectively, and it is necessary to do the same procedure for all images taken in the 5 years period. Finally, calculating the sky signal and star signal by the GAIA when the apertures are placed correctly. Thus, we can record the sky and star signal value for each aperture corresponding LHS33, C1 and C2 in different years.

The photometry process can be completed by GAIA, and it will output the result needed, such as the sky and star signal. One essential point is how the operation work. Initially, what we need to do is the determination of aperture size. Thus, it is necessary to calculate the value of full-width at half-maximum (FWHM) [6]. We only see point sources from the CCD images obtained since the star is so distant. Moreover, due to the effect of Earth’s atmosphere, the starlight would be refracted, so we cannot see relatively clear starlight, which can be regarded as point-spread-function. Therefore, if we want to find the size for a suitable level, we can use slicing to measure and analyse the value of FWHM. For here a suitable aperture radius level, twice the FWHM, is used. The purpose is to make the aperture large enough to enclose all of the light from the star and avoid taking account for background light like the nearby star. After the setting of operation, repeat the same operation for LHS33 and calibration star when we process other CCD images for different years.

3. Results

Until now, all of the data needed have been obtained, including the exact position of Luyten’s star (RA&Dec) and the star signal of LHS33 with related calibration stars. For the proper motion, the data for position obtained is used to calculate the proper motion.

3.1. Determine the proper motion

The proper motion is the relationship between the position and time. Usually, for convention, the Julian Data is used for the date in observation. (1 year = 365.25 Julian days). Table 1 shows the specific converting information with its filter for each image.

| Number | Date          | Filter | Julian date |
|--------|---------------|--------|-------------|
| 1      | 2016 Jan 20 23:56 | Red | 2457408.5 |
| 2      | 2017 Jan 17 23:06 | R_C | 2457771.4 |
| 3      | 2018 Jan 19 00:07 | R_C | 2458137.5 |
| 4      | 2019 Jan 17 20:26 | R_C | 2458501.3 |
| 5      | 2020 Jan 04 01:17 | R_C | 2458852.5 |
| 6      | 2020 Jan 04 01:09 | V   | 2458852.5 |
| 7      | 2020 Jan 04 01:13 | Blue | 2458852.5 |
| 8      | 2020 Jan 04 01:21 | I_C | 2458852.5 |

To determine the proper motion, the data for RA and Dec are also needed. Table 2 shows the position information for LHS33 and its calibration star clear. In addition to this, it is worth noting that the unit for RA is seconds currently and then converted to arcseconds facilitate the calculation.
Table 2. The position information about the target star LHS33 and calibration star C1&C2. The value only takes account for end-figures (only seconds or arcseconds part).

| Image | LHS33  | C1        | C2        |
|-------|--------|-----------|-----------|
|       | RA/s   | Dec/arc   | RA/s      | Dec/arc   |
| 1     | 25.130 | 33.33     | 14.623    | 53.54     | 47.205    | 25.03     |
| 2     | 25.179 | 29.61     | 14.615    | 53.78     | 47.188    | 25.24     |
| 3     | 25.203 | 25.68     | 14.625    | 53.67     | 47.197    | 25.16     |
| 4     | 25.234 | 22.37     | 14.596    | 53.10     | 47.218    | 24.98     |
| 5     | 25.294 | 18.62     | 14.641    | 53.89     | 47.200    | 25.20     |

Next, for convention, convert all RA (second) to RA (arcseconds) by multiple $15 \cos(\delta)$, where $\delta$ is the declination corresponding to its RA position.

Table 3. The information about the date and position has been listed. And these data can be used to plot the relation between RA&Dec and the time since 1st image.

| Image | Julian Date | Time since 1st images | LHS33  | Dec/arcsecs |
|-------|-------------|-----------------------|--------|-------------|
|       |             |                       | RA/arcsecs | Dec/arcsecs |
| 1     | 2457408.5   | 0.00                  | 375.39 | 33.33       |
| 2     | 2457771.4   | 0.99                  | 375.98 | 29.61       |
| 3     | 2458137.5   | 2.00                  | 376.48 | 25.68       |
| 4     | 2458501.3   | 3.00                  | 376.95 | 22.37       |
| 5     | 2458852.5   | 3.95                  | 377.84 | 18.62       |

Due to the explicit list of Table 1 and Table 2, we can find the graph relationship between RA (arcsecs) and time since the first images. The data for Dec(arcsecs) also do the same procedure as RA. After obtaining the best-fit line for both quantities, the slope of each best-fit line is considered to be a proper motion $\mu_\alpha$ and $\mu_\delta$ for RA and Dec. And the total proper motion $\mu$ is to be [7, 8],

$$\mu^2 = \mu_\alpha^2 + \mu_\delta^2$$  \hspace{1cm} (2)

For the plotting graph, Python is used to visualize the relation, and below is the result.

Table 4. The table above is recorded as the combination of a series of parameters information. Including the line slope and intercept for RA&Dec. And the value for proper motion, $\mu_\alpha$ & $\mu_\delta$ with corresponding standard deviation.

| Quantity                   | Value  | Uncertainty | Units       |
|---------------------------|--------|-------------|-------------|
| RA ($\alpha$): line slope | 0.59   | $\pm 0.10$  | arcsecs/y  |
| RA ($\alpha$): line intercept | 375.35 | $\pm 0.10$  | arcsecs    |
| Dec ($\delta$): line slope | -3.70  | $\pm 0.11$  | arcsecs/y  |
| Dec ($\delta$): line intercept | 33.28  | $\pm 0.11$  | arcsecs    |
| $\mu_\alpha$              | 0.59   | $\pm 0.10$  | arcsecs/y  |
| $\mu_\delta$              | -3.70  | $\pm 0.11$  | arcsecs/y  |
| total                     | 3.75   | $\pm 0.11$  | arcsecs/y  |
| Standard deviation - $\alpha$ | 0.14  | ---         | arcsecs    |
| Standard deviation - $\delta$ | 0.16  | ---         | arcsecs    |
From Table 4, we can know the calculated proper motion for RA ($\mu_\alpha$) is $0.59 \pm 0.10$ arcsecs per year and for Dec ($\mu_\delta$) is $-3.70 \pm 0.11$ arcsecs per year. And according to equation (2), the total proper motion $\mu$ is 3.75.

Figure 1 and Figure 2 show the relation of astrometric position and Julian Date explicitly. The value of proper motion is corresponding to the slope of fit-line. From the Figure 1, we can see the relation of RA with the relative date. The equation for fit-line is described as $y = 0.59x + 375.35$, which 0.59 arcsecs/year is $\mu_\alpha$ and intercept is 375.35 arcsecs. From Figure 2, this graph shows the fit-line for Dec is $y = -3.70 + 33.23$, which the -3.70 arcsecs/year is the $\mu_\delta$ and its intercept is 33.23 arcsecs.

**Figure 1.** The relationship between RA and time since first image with error bar and a fit-line.

**Figure 2.** The relationship between Dec and time since first image with error bar and a fit-line.
3.2. Determine the magnitude and colour of Luyten’s star
We define the apparent magnitude to be \( m_{LHS} \) and calibration star is \( m_c \), so the difference between LHS33 and calibration star is expressed as [9],

\[
m_{LHS} - m_c = -2.5 \log(F_{LHS}/F_C) \tag{3}
\]

Which can be simply as,

\[
m_{LHS} - m_c = -2.5 \log(F_{LHS}) + 2.5 \log(F_C) \tag{4}
\]

And so

\[
m_{LHS} = -2.5 \log(F_{LHS}) + k \tag{5}
\]

where \( k = m_c + 2.5 \log(F_C) \) is the calibration constant.

To calculate the value of apparent magnitude (\( m_{LHS} \)) for different filters, the star signal flux should be used in Equation (5) with its calibration constant. Some raw data has been listed as below,

**Table 5.** The raw data about the sky and star flux was obtained from GAIA. These results are through 4 different passbands for LHS33 and its calibration star.

| Image | LHS33 Sky | LHS33 Signal | C1 Sky | C1 Signal | C2 Sky | C2 Signal |
|-------|-----------|-------------|--------|-----------|--------|-----------|
| 05 R_C | 2455.70   | 10398500    | 2470.90| 1335300   | 2471.90| 782960    |
| 06 V   | 664.78    | 332170      | 669.95 | 773240    | 668.29 | 450720    |
| 07 Blue| 479.60    | 143190      | 475.23 | 637340    | 468.32 | 371970    |
| 08 I_c | 384.05    | 2352500     | 367.73 | 686710    | 373.29 | 403220    |

Some results have been listed as below,

**Table 6.** A combination of calculated apparent magnitude with its uncertainty of LHS33 and reference magnitude with its calibration constant k1&k2 though R_C, Blue, V and I_c filter.

| Image | LHS33 calculated mag | C1 Reference Mag | K1 | C1 Reference Mag | K1 |
|-------|----------------------|-----------------|----|-----------------|----|
| 5 R_C | 8.748±0.001          | 8.797±0.005     | 24.111 | 9.378±0.005     | 24.112 |
| 6 V   | 9.707±0.002          | 9.005±0.012     | 23.516 | 9.577±0.010     | 23.503 |
| 7 Blue| 11.332±0.003         | 9.512±0.004     | 24.233 | 10.076±0.034    | 24.211 |
| 8 I_c | 7.158±0.001          | 8.498±0.016     | 23.090 | 9.073±0.025     | 23.087 |

From Table 6, the colour also can be known, V - RC: 0.959 ± 0.003 and V - I_c: 2.549 ± 0.003.

4. Discussion

4.1. The choice for choosing end-figure
Significantly, the unit used in Table 2 is seconds for RA and arcseconds for Dec. Usually, this choice is convenient for the later calculation and avoids unnecessary troubles. For instance, because the only different part of RA is the second rather than hours and minutes. So the critical point of investigation should be focused on the seconds.
4.2. Use of calibration constant and absolute magnitude

Table 5 the value of $k_1$ and $k_2$ are similar and they are within the uncertainty. Because the calibration constant depends on both the apparent magnitude and flux of calibration star, which also ensures the precision of the calibration constant with two reference star, then we can substitute the constant into Equation (5) to calculate the apparent magnitude for LHS33 for different passbands. Furthermore, to keep the consistency for the different observers, the absolute magnitude will be introduced to my results since the apparent brightness depends on the observers’ location. Usually, astronomers assume the absolute magnitude will be at a distance of 10 parsecs from Earth. The equation for converting apparent magnitude to absolute magnitude $M_v$ is below,

$$m_v - M_v = 5 \log(r) - 5$$  \hspace{1cm} (6)

Where $m_v$ is the apparent magnitude of LHS33 in V passband and $r$ is the distance from Earth to LHS33. Rearrange it we obtain,

$$M_v = 5 \log(r) - 5 - m_v$$ \hspace{1cm} (7)

For here, $m_v = 9.707$ (from Table 6) and $r = 3.80$ parsecs

Thus,

$$M_v = 11.80.$$ 

4.3. Comparison of the apparent and absolute magnitude with some known published magnitudes

Comparison with the published data shown as below,

Table 7. The information on published data includes the published magnitude [10] and colours for LHS33 [11].

| Passband | Published magnitude | Published colours |
|----------|---------------------|-------------------|
| $R_C$    | 8.699               | $V - R_C$: 1.173  |
| $V$      | 9.872               |                   |
| Blue     | 11.443              | $V - I_c$: 2.711  |
| $I_c$    | 7.161               |                   |

Overall, the value of apparent magnitude calculated is consistent with published data. The difference for all the passband is within ~1 magnitude. That is also a piece of strong evidence showing the process of aperture photometry is at a reasonable level. The absolute magnitude in V passband is 11.80, which is similar to the value of published. From the result of both magnitude and comparison to the previously published data, we can know the star is relatively faint.

4.4. Comparison of the proper motion for RA and Dec with published data.

The published data has been shown as below [10],

Table 8. A list of the published value of proper motion for RA and Dec.

| Quantity | Value   | Uncertainty | Units              |
|----------|---------|-------------|--------------------|
| Published $\mu_\alpha$ | 572.51  | ±1.50       | milli-arcsecs/y    |
| Published $\mu_\delta$ | -3693.51 | ±0.96       | milli-arcsecs/y    |
The calculated $\mu_\alpha$ is 0.59 arcseconds per year and 590 milli-arcseconds per year after converting the units. Similarly, the calculated $\mu_\delta$ is 3700 milli-arcseconds per year when converting the units as same as the published. From comparing with the published, I find there is consistency between the two types of proper motion.

5. Conclusions
From the results for Table 4 and 6 and Section 4.3 and 4.4, we can deduce that Luyten’s star is a very faint star with an apparent magnitude 9.707 in the V passband. In general, astronomers define the dimmest objects visible in naked eyes to be 6.0. It is hard to observe it based on our naked eyes, even in a clear night. Thus the photometric analysis gives an interpretation of the phenomenon in a scientific way. On the other hand, Luyten’s star possesses a high proper motion based on the observation and analysis. This property is very special compare to most stars in the universe. Furthermore, it is because of the special point. People are interested in studying and observing it. The proper motion in Dec ($\mu_\delta = 3.70$ arcsec/year) can tell us the LHS33 has a significant movement in its declination compare to the background stars. In contrast, a typical value of proper motion is around 0.1. From the comparison, the value of $\mu_\delta$ does appear to be remarkable. However, due to huge amounts of stars existing in the universe, the proportion of high proper motion stars is still taken a large place. For this paper, a specific example focused on LHS33 is given, and certainly, there are many similar properties stars needed to be investigated. Although Luyten catalog gathered plenty of high proper motion stars, many stars are still waiting for detection. Even not only emphasising on one property but also for a variety of properties we need to explore it.

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