CCD PHOTOMETRY OF OPEN STAR CLUSTER M67

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Abstract
In the submitted paper I deal with CCD photometry of the open star cluster M67. This star cluster was observed at the Observatory of the Department of Theoretical Physics and Astrophysics at the Faculty of Science, at Masaryk University in Brno in the four photometric filters. Based on these data colour-magnitude diagrams have been constructed, from which the basic properties of the cluster have been estimated. Considering most of stars that are members of a star cluster has similar age and chemical composition as the Sun, this object is very suitable for observation and study of solar-type stars.

Key words: open star cluster, photometry, colour-magnitude diagrams

1 Introduction
Open star cluster M67 (NGC 2682) is found in a not very significant Cancer constellation. It belongs to the oldest, and in consideration of the stars, to the richest open star clusters. According to Trumpler’s classification, it belongs to the class II 2r, which means that it ranks among a star cluster with low concentration of stars in the middle and middle-range of brightness. It was discovered by Johann Gottfried Koehler in 1779, and independently rediscovered by Charles Messier (1730-1817) on April 6th, 1780. He integrated this star cluster into his catalogue under the sequence number -67th. At this stage of evolution, in the Hertzsprung-Russell diagram, we can clearly see a red giant branch, while the main sequence ends in hot blue stars of the spectral class A or F. According to Cecilia Payne-Gaposchkin (1979), this cluster contains nearly 200 white dwarfs. From the recent studies dealing with CCD photometry of the open star cluster 67 (Vandenberg, 2007), the following parameters result: the age of the star cluster was determined at approximately (3.9 ± 0.2) • 10⁹ years, the distance modulus (m-V-M_V) = 9.7 ± 0.2 magnitude. The same parameters were also published by Balaguer-Nunez et al. (2007). Based on observations of light curves of the five eclipsing binaries and other variable stars, Yakut et al. (2009) determined the age of about 4 • 10⁹ years and the distance of the star cluster (857 ± 33) pc.

2 Material and Methods
The open star cluster was observed by J. Janik and J. Liška from the observatory at the Department of Theoretical Physics and Astrophysics at the Faculty of Science, Masaryk University in Brno, on“ Kraví hora“(mountain), on 28.2.2011 from 19:37:23 to 00:10:38 UT. The main observational instrument was a 0.62 m mirror reflector and the detector was a CCD camera of type SBIG ST-8 Dual CCD Camera with chip KAF-1600 from Kodak. During the observations four filters were used:
- B 14 frames, 50s exposure
- V 14 frames, 50s exposure
- R 14 frames, 50s exposure
- I 14 frames, 50s exposure
2.1 Image processing and correction

For a correct determination of the star cluster’s parameters we need to process those CCD images in order to eliminate the multiplication and additive noise. We also have to calibrate those images, i.e. we have to move from the measured instrumental stellar sizes to the internationally comparable values. The first step, which we had to do, was elimination of the additive noise. In this process, a dark-frame subtraction of the processing image helps us. After this, we get an image, which is not impeded by the dark current. The multiplication noise can be eliminated by dividing the image, corrected off the dark-frame and flat-field. In this case, it is ideal to get more flat-fields and to make an average from them in order to reduce the noise. It is needed to subtract the dark frame from the average flat-field, to obtain zero flat-field. Then, this processing image with the corrected flat-field can be split. This correction may be expressed by the relation published by Buil (1991):

\[ E(x,y,t) = K \frac{R(x,y,t) - N(x,y,t)}{F(x,y,t') - N(x,y,t')} \]  

where \( R(x, y, t) \) is the original image, \( N(x, y, t) \) is the dark-frame of the original image, \( F(x, y, t') \) is the flat-field, \( N(x, y, t') \) is a dark-frame of the measured flat-field, \((x, y)\) are pixel coordinates, \( t \) is the integration time of the processed image, \( t' \) is the integration time of flat-field.

2.2 Photometric calibration

In this way processed images are ready for the instrumental photometry, but we still cannot construct colour-magnitude diagrams or make an analysis of them. Therefore we have to carry out a colour photometric calibration, which means to pass from the values of instrumental stellar sizes obtained from a specific set of filters to the result, which can be gained by usage of standard filters. With the help of the theoretical derivation and with the practical and statistical analysis, it is possible to express the colour photometric calibration with 4 filters by theoretical relations.

\[ m_B - m_B = \zeta_B + \xi \left[ \frac{(m_B - m_V) + (m_B - m_R)}{2} \right], \]  
\[ m_V - m_V = \zeta_V + \eta \left[ \frac{(m_V - m_B) + (m_V - m_R)}{2} \right], \]  
\[ m_R - m_R = \zeta_R + \chi \left[ \frac{(m_R - m_B) + (m_R - m_V)}{2} \right], \]  
\[ m_i - m_i = \zeta_i + \psi \left[ \frac{(m_i - m_B) + (m_i - m_R)}{2} \right], \]

Stellar sizes, which are expressed in magnitude with large index mark catalogue of values (standard stars), and with small index measured values. Since the spectral transmittance of filters can be expressed as a linear combination of spectral transmissions of standard filters, the colour photometric calibration of images can be done with the help of linear regression. For this process were used 14 comparative stars, whose catalogue values were obtained from the site of observers of variable stars. Therefore, it was possible to calibrate stellar sizes in the filter R, which are not available in most of works. We have, thus, resulting calibration equations in the form:

\[ m_B = m_B - (1,867 \pm 0,228) + (0,146 \pm 0,035) \cdot (m_B - m_V), \]  
\[ m_V = m_V - (1,218 \pm 0,298) - (0,101 \pm 0,024) \cdot (m_V - m_R), \]  
\[ m_R = m_R - (1,056 \pm 0,259) - (0,085 \pm 0,021) \cdot (m_V - m_R), \]  
\[ m_i = m_i - (1,310 \pm 0,321) + (0,048 \pm 0,012) \cdot (m_R - m_i). \]
Catalogue stellar sizes of comparative stars do not appear in those equations anymore, because here general calibration equations for all the stars of the given field are concerned.

3 Results and discussion

Colour-magnitude diagrams for the individual colour indexes (B-V), (V-R), (V-I) were created on the basis of CCD photometry. They are illustrated with theoretical isochrones in Figures 1, 2, 3, where on the vertical axis is placed the measured stellar size in the filter V and on the horizontal axis is the corresponding colour index. On these diagrams can be seen the main sequence directing from the lower right to upper left corner. On the diagrams a shift from the main sequence can also be seen, and the giant branch, which implies that it is a very old open star cluster. The distance and age of open star clusters can be determined by comparison of the process of main sequence with a theoretical model. Theoretical isochrones used in this work were published by Bertelli et al. (1994), and include models for different chemical composition and age. Position of an isochrone turnover from the main sequence in the colour-magnitude diagram will help us to determine the age of star clusters. The age of the star cluster - \(10^{9.6} = 3.98 \times 10^9\) year was determined by colour-magnitude diagrams with the theoretical isochrones. The chemical composition of the star cluster, where the proportion of helium is \(Y = 0.25\) and the proportion of heavier elements - \(Z = 0.008\), was also determined.

For the calculation of the distance of star cluster, it is necessary, in our case, to know the distance modulus. We will get this distance modulus from the shift of the main sequence obtained from observation of theoretical isochrones. For better illustration of the distance was found out the average value of the distance modulus from Figures 1, 2, 3, - and it is \(m_V-M_V = (9.7 \pm 0.12)\) mag for all three colour indexes. The distance of the star cluster can be determined by a modified Pogson’s equation:

\[
d_{pc} = 10 \frac{m_V-M_V + 5}{5}, \quad (10)
\]

where \(m_V-M_V\) is the distance modulus and \(d\) is the searched distance of star clusters in parsecs. From this relation, we get the distance of the star cluster after substituting of the value of a distance modulus \(d=(871 \pm 20)\)pc.

![Fig. 1 Colour-magnitude diagram of the open star cluster M67, which expresses the dependence of the stellar size in the filter V on the colour index (B-V).](image)
3.1 Estimation of interstellar reddening

The value of interstellar extinction can be approximated by three-colour-magnitude diagram (in this case, the B-V on V-R) for the measured and theoretical values. This value is determined by the displacement of measured main sequence from the main theoretical sequence, which is not affected by the extinction. In Figure 4, there is created dependence of the colour indexes B-V and V-R. When using a linear regression, it is possible to determine approximate value of the interstellar extinction.
Fig. 4 Dependence of the colour indexes B-V and V-R to determine the value of interstellar extinction.

The line re-laid by measured values can be described by the equation:

\[ B - V = (1,608 \pm 0,131) \cdot (V - R) + (0,089 \pm 0,0144), \]  

and the linear regression of the theoretical dependence of colour index (B- V) on (V-R) from the work of Bertelli et al. (1991) can be described by the equation:

\[ B - V = (1,569 \pm 0,036) \cdot (V - R) + (0,108 \pm 0,021). \]

Directives of both lines only slightly differ one from another and the shift in the direction of colour index (B-V) gives an approximate value of the interstellar reddening (colour excesses), E(B-V). This shift is not constant throughout the whole process, its most probable value may be E(B-V) = 0.039 mag.

4 Conclusion

Based on CCD photometry, characteristics of open star cluster M67 has been determined in this work. A total number of 205 stars have been photometrically processed and all measured values have been reduced and calibrated so thoroughly and in the correct manner that the resulting diagrams show marked and clearly defined main sequences. On the colour-magnitude diagrams can be seen the main sequence directed from the lower right to upper left corner, which means that it is a very old open star cluster, what the results really confirmed. By fitting of theoretical isochrones into the measured values the age has been determined to 3.98 \times 10^9 \text{ year}, where the theoretical isochrone with a proportion of helium \( Y = 0.25 \) and proportion of heavier elements \( Z = 0.008 \) was the most suitable. We also obtained the average value of the distance modulus \( m_V-M_V=(9,7\pm0,12) \text{ mag} \), which indicates the distance to \( d=(871\pm20) \text{ pc} \), by calculation of Pogson’s equation. The value of interstellar reddening, determined by the shift of the measured main sequence from the main theoretical sequence, is \( E(BV) = 0.039 \text{ mag} \). In this case we can get more accurate value by fitting the curve corresponding to the shape of the measured main sequence.
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5 References