CCD BV photometry of three southern galactic open clusters using Faulkes Telescope South

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We present results of CCD photometry of the southern galactic open clusters Ru77, Ru78 and Ru83 obtained with Faulkes Telescope South. We believe these are the first published colour–magnitude and Herzsprung–Russell diagrams of these clusters based on the BV photometric system.

Introduction

The colour–magnitude diagram (CMD) of a star cluster is a variant of the familiar Herzsprung–Russell diagram (HRD) and provides information about the state of evolution of stars in the cluster in relation to the stellar main sequence. The CMD plots the apparent visual magnitude of stars in the cluster vertically against their observed colour horizontally with blue (hot) stars to the left and red (cool) stars to the right. The apparent visual magnitude and observed colour are conventionally represented by the Johnson V magnitude and B–V colour index respectively. The CMD is therefore based on the observational data we measure here on Earth about the stars in the cluster. This can be contrasted with the HRD which plots absolute visual magnitude Mv against intrinsic colour index $(B-V)_0$. These parameters represent the physical properties of the stars in an absolute sense, deduced from their observed brightness and colour and knowing the distance of the cluster and any interstellar reddening. Data from all clusters can therefore be combined in a single HRD.

It is usually assumed that the stars in a cluster have all formed at more or less the same time. They initially lie on what is called the main sequence in the HRD. This is a curved band stretching from the lower right of the diagram to the upper left. Hotter, more massive stars form towards the top of the sequence and cooler, less massive ones towards the lower end. As the stars in the cluster evolve their brightness and colour changes so they move within the diagram. Since the most massive stars evolve most rapidly, these will be the first to move away from the main sequence. As these large stars evolve they become redder and so move towards the upper right of the diagram. Eventually, as shown in Figure 1, the top of the main sequence curves over towards the right and the position of the bend gradually travels down the main sequence as the cluster ages and progressively less massive stars start to evolve.
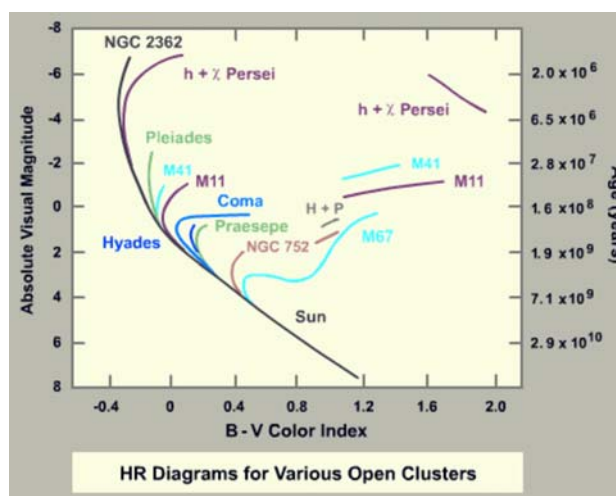

Figure 1. Herzsprung–Russell diagram showing open clusters at different stages of evolution. *Reproduced with the agreement of M. Guidry, University of Tennessee.*

By plotting the CMD of a star cluster, it is therefore possible to see whether the cluster is relatively young, in which case most of the stars will still lie on the main sequence, or older, in which case the trajectory of the main sequence will have started to curve over towards the right. Figure 2 shows CMDs for a young cluster (M45, the Pleiades) and an older cluster (NGC 188). These were obtained from the *WEBDA*
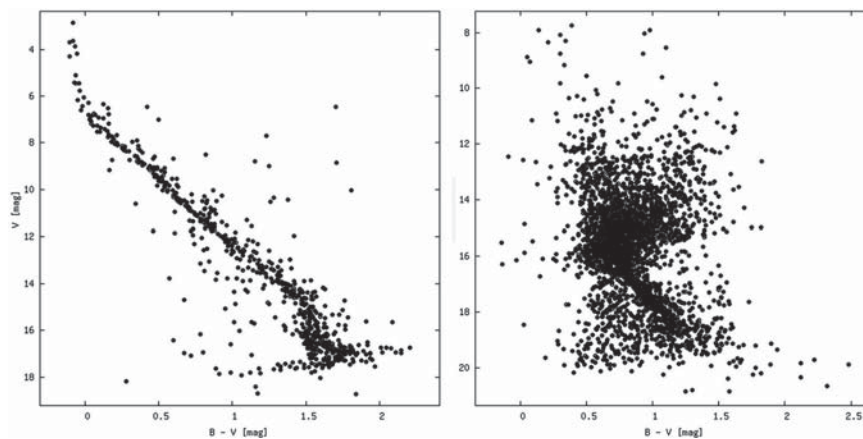

Figure 2. Colour–magnitude diagrams for the young cluster M45 (left) and an older cluster, NGC 188 (right). *Courtesy WEBDA.*
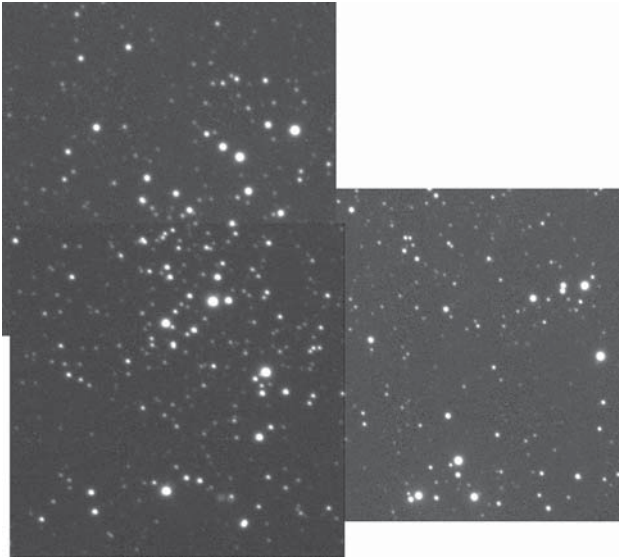
Figure 3. Composite V-band image of Ru83 obtained with Faulkes Telescope South. (N top, E left, each frame 4.7 arcmin square).

Figure 4. Topaktas & Fenkart[2] numbering diagram for the field of Ru83 (not all numbered stars are considered to be cluster members).

website,[1] which provides extensive information on galactic open star clusters.

CMDs were first obtained for many clusters with photographic plates exposed using the RGU photometric system. RGU is a photographic photometric system, developed and used at the Astronomical Observatory of the University of Basel in the 1930s. Generally, the published magnitudes and colours are based on a small number of plates, and the scatter in the photometric diagrams is rather large. Since the advent of the Johnson UBV photometric system in the 1950s and the replacement of photography by CCD imaging, many clusters have been re-measured so most clusters in *WEBDA* now have UBV data. However a number of open clusters, particularly those at more southerly declinations, still only have data in *WEBDA* which are based on RGU photographic photometry obtained many years ago.

The project

This project was conceived as a way of giving school pupils at Kennet School in Thatcham, West Berkshire, practical experience of real scientific research. Our aim was to make the necessary observations and to use the results to construct both the CMDs and HRDs for some galactic open clusters. We chose three southern galactic open clusters, Ru77, Ru78 and Ru83, named after the Czech astronomer Jaroslav Ruprecht who first catalogued them in 1958. They were chosen as their CMDs in *WEBDA* are based on RGU photometry by Topaktas & Fenkart (T&F)[2] using photographic plates taken in 1974 and, as far as we could discover, no data about them based on current photometric methods and standards are available. The instrument we used was the Faulkes Telescope South (FTS) at Siding Spring in Australia, which could be operated remotely from the school over the internet. The Faulkes
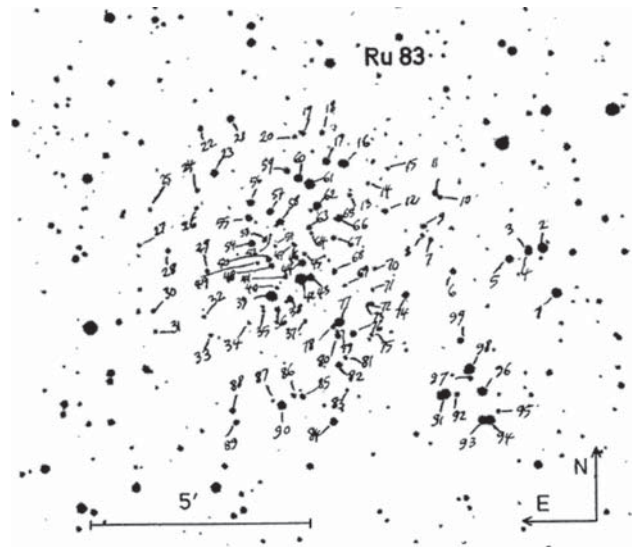
Telescopes are two 2m robotic telescopes equipped with CCD cameras located in Hawaii and Australia, and operated by the Faulkes Telescope Project[3] for use by schools in the UK.

Imaging

The Kennet School astronomy group, comprising science teacher AD and sixth form pupils AS and GF, obtained FTS images of cluster Ru78 while DB obtained images of clusters Ru77 and Ru83. The images were acquired during FTS observing sessions in 2008 February and 2008 May. Since the FTS field of view is only 4.7 arcmin square, three image positions were needed to cover the extent of Ru77 and Ru83 and four were required for Ru78, the largest of the three clusters. Because of a slight pointing inaccuracy in the telescope control system, the small image size and the limited number of images which could be obtained during each observing session, a few stars at the edges of the clusters were not covered by our images. At each position, 60sec exposures were taken using B and V filters. These contained well exposed images of bright stars (with the exception of the two brightest stars in Ru78 which were saturated) while adequately recording the faintest stars required. Figure 3 shows a composite of the three V-band images for Ru83.

Table 1. Numbers of stars measured in each cluster

Cluster	Stars measured	Of these, no. of cluster members
Ru77	79	36
Ru78	105	38
Ru83	77	35

T&F give diagrams which number stars in the field of each cluster. Figure 4 reproduces the T&F numbering diagram for the field of Ru83. Their paper also identifies which stars in the field they consider to be members of the cluster, although no logic explaining this assignment is given. Reading other papers, it appears that this assignment is usually made on a combination of position in the CMD and distance from the centre of the cluster. We have adopted T&F's assignment of cluster members for each cluster. For example, for Ru83, these are 2, 5, 6, 8, 9, 11, 12, 14, 17, 21, 22, 23, 24, 25, 26, 27, 28, 31, 37, 40, 41, 47, 51, 52, 53, 56, 57, 58, 59, 60, 62, 63, 64, 67, 69, 75, 76, 81, 83, 87, 88, 92, 93 and 96.

Photometry

Aperture photometry was carried out for stars in Ru78 using the *SalsaJ* software[4] provided by the Faulkes Telescope support team and for stars in Ru77 and Ru83 using the commercial software *AIP4WIN*.[5] To choose a photometric aperture radius, a growth curve of the variation of integrated star intensity with aperture radius was plotted to find the smallest radius which would include almost all the light from stars in the images. In our case this radius was 15 pixels which was approximately twice the full width at half maximum height (FWHM) of stars in the FTS images. All stars listed by T&F which fell within our images were measured, with the exception of stars which were either too close together to be cleanly resolved or were contaminated by a much brighter nearby star. The intensity values provided by the photometry software for each star were then converted into B and V-band instrumental magnitudes, b and v, using the conventional formula

$$\text{instrumental magnitude} = -2.5\log_{10}(\text{intensity}).$$

A sample of stars measured with *SalsaJ* was re-measured with *AIP4WIN* to confirm consistency between the two analysis procedures. Instrumental magnitudes from *SalsaJ* and *AIP4WIN* differed on average by ~0.02 mag in both B and V. This was similar to the spread in instrumental magnitudes of stars which were measured in more than one image. We therefore infer that the uncertainty in our instrumental magnitudes is ~0.04 mag. The two saturated stars in Ru78 (54 and 94) were omitted from the subsequent analysis. The number of stars measured in the field of each cluster is given in Table 1.

Magnitude calibration and transformation

In order to plot CMDs for each cluster, we needed to convert the instrumental magnitudes, b and v, for each star to apparent magnitudes, B and V, on the Johnson UBV photometric standard system. To do this we needed to transform

Table 2. Tycho-2 stars used to calibrate magnitudes in each cluster

Cluster	Tycho-2 identifier	BT mag	VT mag	B_J mag	V_J mag
Ru77	TYC 8588 0096	11.056	10.492	10.950	10.432
Ru77	TYC 8588 3640	11.666	11.506	11.628	11.487
Ru77	TYC 8588 1258	12.769	11.760	12.546	11.662
Ru78	TYC 8584 2797	12.110	11.483	11.989	11.417
Ru78	TYC 8584 2593	11.916	11.502	11.844	11.456
Ru83	TYC 8602 0188	13.252	12.141	12.999	12.034

the instrumental magnitudes to account for slight differences between the spectral response of the FTS camera and filters and the Johnson standard. We also needed to establish zero points of the B and V magnitude scales for each night of observation.

Transformation coefficients Tb (defining the relationship between B–b and b–v) and Tv (for V–v and b–v) were obtained by analysing images of Landolt standard fields taken on the nights of observation.

To determine the B and V magnitude zero points, Zb and Zv, for each night of observation, we selected the brightest unsaturated stars in each cluster which could be found in the Tycho-2 catalogue. These calibration stars are listed in Table 2. The BT and VT magnitudes of these stars in the Tycho-2 catalogue were obtained from *VizieR*[6] and were converted to Johnson B and V magnitudes, B_J and V_J, using published conversion formulae.[7,8] For stars of these magnitudes, the Tycho-2 catalogue gives standard errors in BT and VT of ±0.1 mag. As we were not able to locate any more accurate photometry covering these clusters, we have adopted the Tycho-2 magnitudes for our calibration.

The zero points were calculated using the formulae

$$Zb = B_J - b - Tb(b{-}v) \text{ and } Zv = V_J - v - Tv(b{-}v)$$

where B_J and V_J are the Johnson magnitudes of the Tycho-2 stars from Table 2 and b and v are their measured instrumental magnitudes. Mean B and V zero points were calculated for each cluster and each observing session using all of the Tycho-2 stars measured in that cluster.

B and V magnitudes for the stars in each cluster were then calculated from their instrumental magnitudes, b and v, using the transformation coefficients, Tb and Tv, and magnitude zero points, Zb and Zv, using the formulae

$$B = b + Tb(b{-}v) + Zb \text{ and } V = v + Tv(b{-}v) + Zv.$$

Colour–magnitude and Herzsprung–Russell diagrams

CMDs for each cluster were produced by plotting V against B–V as shown in Figure 5.

Since *WEBDA* provides the distance modulus μ and the colour excess or reddening E(B–V) for each cluster, it is possible to generate HRDs for each cluster by calculating the absolute visual magnitude Mv and the intrinsic colour index $(B{-}V)_0$ for each star using the formulae
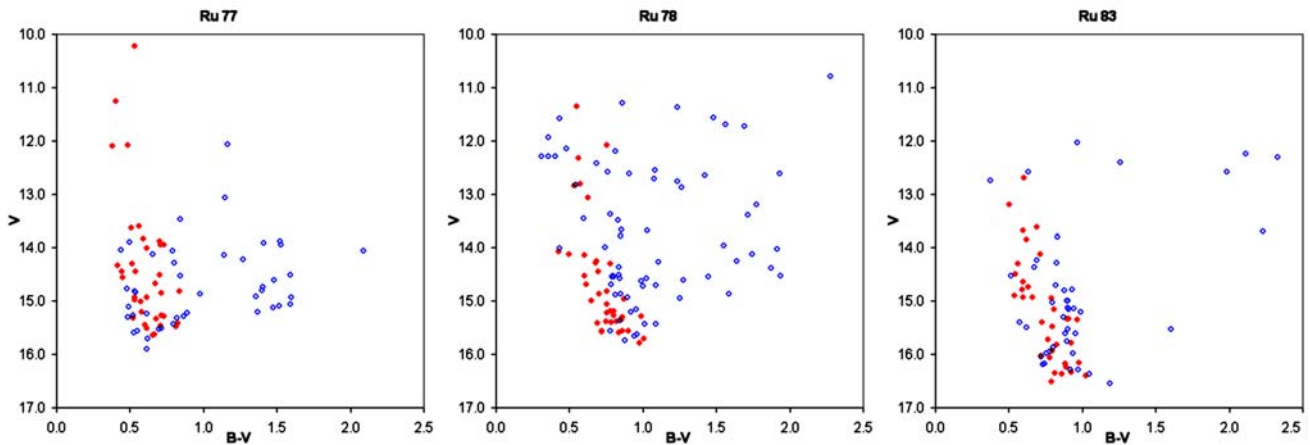
Figure 5. Colour–magnitude diagrams for clusters Ru77, Ru78 and Ru83. Stars assigned to the clusters by Topaktas & Fenkart[2] are marked as red filled circles and non-cluster stars as blue open circles.

$$Mv = V - \mu \text{ and } (B-V)_0 = (B-V) - E(B-V)$$

Finally, the HRDs for each cluster were produced by plotting Mv against $(B-V)_0$ as shown in Figure 6.

Also plotted in each figure is the Zero Age Main Sequence (ZAMS) trajectory,[9] which is the position in the HRD where stars which have just begun the process of hydrogen fusion are located. As stars begin to age, they move to the right of the ZAMS trajectory. We would therefore expect the stars in these clusters to be located slightly to the right of the ZAMS trajectory and as they evolve to move further to the right away from the ZAMS. This happens to the most massive stars first. These are also the brightest stars and so are located near the top of the HRD. Our results appear to be consistent with the assignment of cluster members by T&F as we find these stars predominantly lying close to the ZAMS trajectory. A small number of bright cluster stars at the top of each diagram lie more to the right of the ZAMS trajectory, indicating that these clusters are beginning to evolve but are still relatively young. Comparing the distances of the stars in each cluster from the ZAMS, it appears that the cluster which has evolved least is Ru77 and that which has evolved the most is Ru83. This is consistent with the ages of the three clusters given in *WEBDA*. Table 3 lists the distances and ages of each cluster given by *WEBDA*.

Table 3. Distance and age of each cluster, from *WEBDA*

Cluster	Distance (kiloparsec)	Age (million years)
Ru77	4.13	31.6
Ru78	1.64	97.1
Ru83	2.46	281.8

Conclusion

Using the facility provided by the Faulkes Telescope Project to remotely image objects from schools in the UK, we have produced the first colour–magnitude and Herzsprung–Russell diagrams of three southern galactic open clusters, Ru77, Ru78 and Ru83, using the Johnson UBV photometric system.
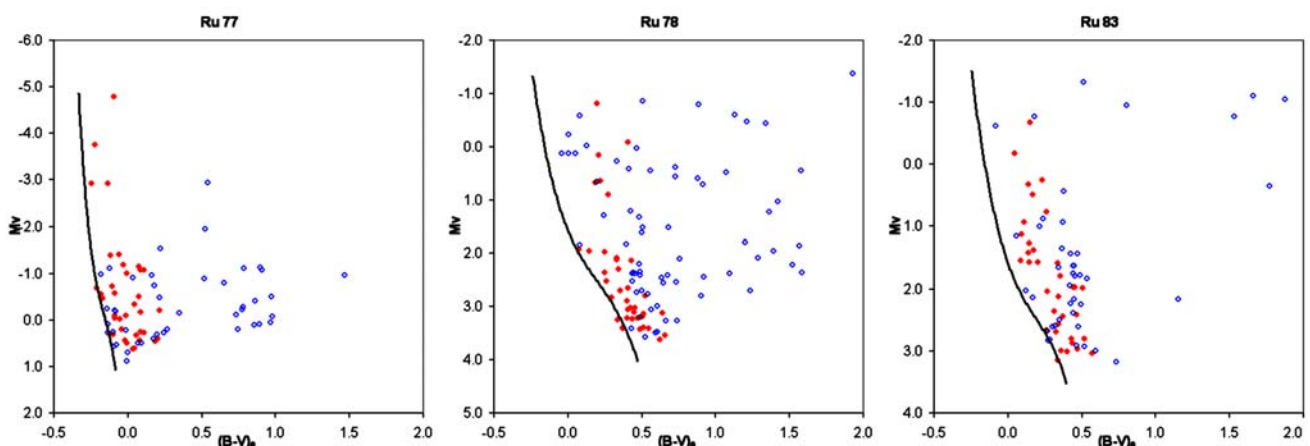
Acknowledgments

Figure 6. Herzsprung–Russell diagrams for clusters Ru77, Ru78 and Ru83 from our data. Colour coding is the same as in Figure 5. The lines represent the trajectory of the Zero Age Main Sequence in the region of each cluster.

grateful to the referee for helpful comments which have improved the paper.

References

1   *WEBDA*: **http://www.univie.ac.at/webda/**
2   Topatkas L. & Fenkart R. P., *Astron. Astrophys. Supp.* **49**, 475 (1982)
3   Faulkes Telescope Project: **http://faulkes-telescope.com/**
4   *SalsaJ*:   **http://faulkes-telescope.com/files/faulkes-telescope.com/archive/photometry/Lifecycle_stars/photometry_salsaj_SR.pdf**
5   *AIP4WIN*: Berry R. & Burnell J., *The Handbook of Astronomical Image Processing (2nd edn)*, Willmann–Bell, 2005
6   *VizieR* Service: **http://webviz.u-strasbg.fr/viz-bin/VizieR**
7   Mamajek E. E., Meyer M. R. & Liebert J., *Astron. J.*, **124**(3), 1670 (2002)
8   Mamajek E. E., Meyer M. R. & Liebert J., *Astron. J.*, **131**(4), 2360 (2006)
9   Mermilliod J. C., *Astron. & Astrophys.*, **97**, 235 (1981)