The old open clusters Saurer A, B and C revisited

Giovanni Carraro\textsuperscript{1} and Gustavo Baume\textsuperscript{1,2} \textsuperscript{†}
\textsuperscript{1}Dipartimento di Astronomia, Università di Padova, Vicolo dell’Osservatorio 2, I-35122 Padova, Italy
\textsuperscript{2}Facultad de Ciencias Astronómicas y Geofísicas de la UNLP, IALP-CONICET, Paseo del Bosque s/n, La Plata, Argentina

ABSTRACT
We report on deep (V ≈ 24.0) \(V\)I CCD photometry of 3 fields centered in the regions of the old open clusters Saurer A, B and C. In the case of Saurer A, which is considered one of the oldest known open cluster, we also provide a comparison field. From the analysis of the photometry we claim that Saurer A is as old as M 67 (≈ 5 Gyrs), but more metal poor (Z=0.008). Moreover it turns out to be the open cluster with the largest galactocentric distance so far detected.

As for Saurer B, it closely resembles NGC 2158, and indeed is of intermediate-age (1.8-2.2 Gyrs) and significantly reddened. In this case we revise both the age and the distance with respect to previous studies, but we are not able to clearly establish the cluster metal abundance.

Finally, Saurer C has an age of about 2 Gyrs, but we emphasize that the precise determination of its properties is hampered by the heavy field stars contamination.

Key words: Open clusters and associations: general – open clusters and associations: individual: Saurer A, B and C - Hertzsprung-Russell (HR) diagram

1 INTRODUCTION
Saurer et al. (1994) identified 6 star concentrations by inspecting POSS or ESO/SERC atlas, which they suggest might represent hitherto uncatalogued star clusters, which to date have not been included in any open clusters catalog (Dias et al. 2002).

Preliminary photometry of all these star concentrations have been recently published by Frinchaboy & Phelps (2002, FP02 hereinafter). Their results can be summarized as follows:

- Saurer A, B and C are old open clusters with ages greater than 2.5 Gyr. In particular Saurer A is marked as a very promising target for further studies due to the combination of his very large distance and age;
- Saurer E is probably not a physical cluster;
- Saurer D and F finally are intermediate age open cluster, with ages between 1 and 2 Gyr.

Due to the relevant importance of the oldest open clusters for our understanding of the formation and early evolution of the Galactic disk (Janes & Phelps 1994, Carraro & Chiosi 1994, Friel 1995, Carraro et al. 1998, Bragaglia et al. 2000), we decided to obtain new, better quality and deeper photometry of the oldest clusters in this sample, namely Saurer A, B and C (see Table 1), to better constrain their fundamental parameters.

Moreover, instead of deriving ages from a so-called Morphological Age Indicator (MAI, Janes & Phelps 1994), we are presenting a different approach to the determination of all the clusters basic parameters, which is based on the comparison of the photometry with theoretical models.

The plan of the paper is as follows. Sect. 2 illustrates the observation and reduction strategies. Sections 3 to 5 are dedicated to the discussion of our data for Saurer A, B and C, respectively. In these Sections we derive estimates of radii, distances, ages and reddenings. Finally, Sect. 6 summarizes our findings.

| Name | \(\alpha_{2000}\) | \(\delta_{2000}\) | \(l\) | \(b\) |
|------|-----------------|-----------------|-----|-----|
| Saurer A | 07:20:56 | +01:48:29 | 214.61° | +7.21° |
| Field | 07:18:18 | +01:53:43 | 214.31° | +6.84° |
| Saurer B | 08:25:28 | -39:38:02 | 257.95° | -1.06° |
| Saurer C | 10:41:25 | -55:18:20 | 285.05° | +2.98° |

\textsuperscript{†} email: giovanni.carraro@unipd.it (GC); baume@pd.astro.it (GB)
Figure 1. A DSS image centered on Saurer A. The field of view is 10 squared arcmin. North is up, East on the left.

2 OBSERVATIONS AND DATA REDUCTION

CCD $V\ I$ observations were carried out with the new EMMI read arm camera on board NTT at ESO, La Silla, in the photometric night of December 9, 2002 and in sub-arcsec seeing conditions. The new camera has a mosaic of two 2048 $\times$ 4096 pixels CCDs which samples 9.9 $\times$ 9.1 arcmin in the sky having a pixel scale of 0$''$.332 (2 $\times$ 2 binning).

Details of the observations are listed in Table 2 where the observed fields are reported together with the exposure times, the typical seeing values and the air-masses. Figs. 1 to 4 show the finding charts for Saurer A, B, C and the comparison field, respectively, taken from the DSS-2‡ archive. The data has been reduced with the IRAF§ packages CCDRED, DAOPHOT, and PHOTCAL using the point spread function (PSF) method (Stetson 1987). The calibration equations obtained by observing Landolt (1992) PG 0918+029, SA 098-562, SA 101-424 and PG 0942-029 fields observed along the night, are:

\[
v = V - 0.560 \pm 0.023 - (0.058 \pm 0.023) \cdot (V - I) + 0.135 \cdot X
\]

\[
i = I - 0.258 \pm 0.066 - (0.063 \pm 0.070) \cdot (V - I) + 0.048 \cdot X
\]

where $VI$ are standard magnitudes, $vi$ are the instrumental ones, and $X$ is the airmass. The standard stars in these fields provide a very good color coverage. For the extinction coefficients, we assumed the typical values for La Silla observatory.

The photometry turns out to be quite accurate with global errors (zero point, PSF fitting and aperture correction errors) amounting to less than 0.10 mag in magnitude and 0.15 mag in colour down to $V \approx 23.0$.

The final photometric data are available in electronic form at the WEBDA¶ site.

Our photometry extends down to $V = 14$, and therefore results to be about 2 mag deeper than FP02. The photometric accuracy, excellent seeing conditions and good pixel scale allow us to properly study very faint and contaminated objects like those ones in the present study.

‡ Second generation Digitized Sky Survey, http://cadcwww.dao.nrc.ca/cadchwin/getdss
§ IRAF is distributed by NOAO, which are operated by AURA under cooperative agreement with the NSF.
¶ http://obswww.unige.ch/webda/navigation.html
The open clusters Saurer A, B and C

3 THE OPEN CLUSTER SAURER A

3.1 Cluster radius

Saurer A appears as a very weak concentration of stars (see Fig. 1), with a size of a few arcmin. In order to infer a more robust estimate of the cluster radius, we performed star counts by using our CCD data (1500 stars). We derived the surface stellar density by performing star counts in concentric rings 15 arcsecs in size (46 pixels) around the visual cluster center, and then dividing by their respective surfaces. Our aim is to find the region where the cluster clearly emerges over the field. The result is shown in Fig. 5. Here we plot the radial density profile for the cluster (solid symbols) as a function of the limiting magnitude. We performed star counts also in the comparison field, by simply computing the density of field stars down to the same limiting magnitude. The cluster does not emerge much from the field when considering $V_{\text{lim}} = 19$, which means that the cluster is very poorly populated by bright stars. At dimmer magnitudes, the cluster clearly emerges from the field up to $R \approx 1.3$ arcmin, that we shall consider as the cluster radius in the following analysis.

3.2 The Colour-Magnitude Diagram

In Fig. 6 we present the CMDs of Saurer A (left panel) and the comparison field (right panel). The two CMDs look quite similar, and there is no signature of a star cluster by considering the stars in the two fields altogether. The only significant difference is the blue edge of the Main Sequence between 19 and 22 mag, which is much more populated in the cluster than in the field, and which can be interpreted as a cluster sequence. To clarify this point, we consider only the stars in a circle 1.7 arcmin in radius (somewhat larger than the cluster radius) wide centered in the cluster center, and we compare the derived CMD with its counterpart in the field. These regions have been selected to match the circles in Fig. 1 in FP02.

The result is shown in Fig. 7, from which we see that actually a cluster exists, and the CMD looks like that one from
FP02, although we have more stars, and the MS is 1 mag more extended. The exact shape of the CMD is however difficult to understand, at the point we are not able to distinguish neither a Red Giant Branch nor a clump. In particular the detection of a clump at $V=16.7$, $(V-I) = 1.15$ by FP02 is suspicious, provided the almost similar stars distribution of the cluster and the field in the upper part of the CMD. It is therefore clear that from this CMD it is not possible to derive reasonable estimates of the cluster parameters.

To better deal with field stars contamination we then consider only the stars confined within 0.8 arcmin from the cluster center. (see Fig. 8) Here the cluster appears very nicely and the contamination of foreground stars is negligible (see also the field CMD in the right panel). The MS turn off (TO) is located at $V=19.0$, $(V-I)=0.80$, as in FP02. The MS extends for 3.5 mag, and shows two probable gaps...
The open clusters Saurer A, B and C

5

Figure 10. Age uncertainty for Saurer A (only stars within 0.8 arcmin from the cluster center are considered). The solid line is a 5 Gyr isochrone for Z=0.008 metallicity, the dashed line and dotted line are 6.0 and 4.0 Gyr isochrones for the same metallicity, respectively. See tex for more details.

at $V=19.25$ and $V=21.0$ A sequence of binary is also visible red-ward the MS. There are still a few interlopers, but the upper part of the CMD appears now sufficiently clear, although poorly populated. It is in fact possible to see some RGB stars and a probable clump populated by 3 stars at $V=16.9$, $(V-I)=1.1$.

3.3 Basic parameters

We derive Saurer A fundamental properties by comparing the CMD with theoretical isochrones from Girardi et al. (2000). The choice of this set of models is motivated by the need to keep the age, distance and reddening determinations in the same scale of a series of previous papers on the same subject (see for instance Carraro et al. 2002 and references therein). This is quite a basic constraint, especially when old open clusters are used as tracers of the Galactic disk properties and evolution (see the discussion in Carraro et al. 1998), where the homogeneity of the sample is a fundamental need.

In the following analysis we are going to consider only the stars within 48 arcsecs. The best fit isochrone solution is shown in Fig. 9, where we over-imposed a 5 Gyr isochrone for Z = 0.008 metallicity. We have tried several combinations of ages and metallicities, but none provides a reasonable fit like this.

For the sake of illustration we over-plot in Fig. 9 also the solar metallicity isochrone which provides the most reasonable fit (dashed line). This isochrone is for an age of 6.3 Gyrs, and has been shifted by $E(B−V)=0.09$ and $(m−M_V)=15.6$. However, while the TO is nicely reproduced, both the MS and the most evolved region of the CMD are poorly accounted for.

To better bracket the metal content of the cluster we also over-imposed the Z=0.004 isochrone which better fits the data, although this metallicity would be quite low and unexpected for population I objects. The best fit (dotted line in Fig. 9) is obtained for an age of 4.5 Gyrs, a reddening $E(B−V)=0.20$, and a distance modulus $(m−M_V)=16.2$. The fit is good also in this case, the MS is actually a bit bluer, and in principle one could increase a bit the age to lower the distance between the TO and the RGB bottom, but in this way the clump would become too bright. Notice (see Fig. 9) that the theoretical clump is already brighter than the observed one at 4.5 Gyrs.

Therefore we opted for a half solar metal abundance. The fit with the Z=0.008 isochrone has been obtained by shifting the isochrone by $E(V−I)=0.18$ and $(m−M_V)=16.0$. These values are in nice agreement with FB02. To get an estimate of the age uncertainty we have over-imposed to the data a younger and older isochrone for Z=0.008 metallicity. The result is shown in Fig. 10. In this figure the solid line is the 5 Gyr best fit isochrone, whereas the dotted line and the dashed line are a 4 and 6 Gyr isochrones, respectively. By keeping the isochrone close to the cluster TO, the evolved region shows what one expects, namely a bluer RGB at older ages, and a dimmer clump at younger ages. From this figure we estimate an age uncertainty less than 1 Gyr.

FB02 uses the clump as distance indicator, by assuming that the clump really exists and that its position does not depend...
neither on age nor on metallicity. The fact that the clump can be used as distance indicator is quite well known. However we restrain to use it mainly because - as shown by Girardi & Salaris (2001) - the clump position is a function of age and metallicity. This latter parameter in particular cannot be robustly constrained with the available data.

We get an absolute distance modulus $(m - M)_0 = 15.6$. As a consequence, Saurer A turns out to be 13.2 kpc far from the Sun, and by adopting $R_⊙ = 8.5$ kpc, its rectangular coordinates are: $X = 19.3$, $Y = -7.4$ and $Z = 1.7$ kpc, respectively. Therefore Saurer A is the most peripheral open cluster to date, and lies very high on the Galactic plane for an open cluster.

In conclusion, from our photometry we better constrain Saurer A basic parameters. In particular we refine the size and the age of the cluster, we suggest that it is metal poor, and basically confirm the reddening and distance already found by FB02. As for the age, this is not an unexpected result. It is very well known that MAI (Janes & Phelps 1994) tends to over-estimate the age of a cluster, and can be used only as a qualitative indication of the relative age between two or more clusters (see the discussion in Carraro et al. 1999 and FB02).

Figure 12. Left upper panel: CMD of Saurer B for all the detected stars. Right upper panel: CMD of Saurer B for all the stars within the cluster radius. Left lower panel: CMD of Saurer B for all the stars within 1.0 arcmin from the cluster center. Right lower panel: CMD of the stars located in a ring with the same area as the cluster central part, and meant to represent the field population.
4 THE OPEN CLUSTER SAURER B

4.1 Cluster radius

Saurer B appears as a faint concentration of stars as Saurer A (see Fig. 2), although somewhat more extended and loose. In order to infer a more robust estimate of the cluster radius, we performed star counts by using our CCD data (2200 stars). We derived the surface stellar density by performing star counts in concentric rings 15 arcsecs in size around the visual cluster center, and then by dividing by their respective surfaces. In this case we do not have a comparison field, so it is more cumbersome to derive a firm estimate. However, by looking at Fig. 11, one can conclude along the same vein of the discussion for Saurer A that the cluster emerges over the field as a group of faint stars, and that the cluster radius is \( \approx 1.5 \) arcmin, a value which confirms the visual inspection of Fig. 2.

4.2 The Color-Magnitude Diagram

In Fig. 12 we present various CMDs of Saurer B as a function of the distance from the cluster center. In the upper left panel the CMD for all the detected stars is shown. Here the cluster is barely visible and the CMD is dominated by the MS of the Galactic disk population. At odds with Saurer A, this cluster is in fact located quite low in the Galactic disk. Having estimated a radius of \( \approx 1.5 \) arcmin, we present also the CMD for the star in this region (upper right panel), which basically shows the same features of the previous CMD, although an important fact can be noticed: while the blue part of the CMD in this case becomes narrower and better defined, the red part does not change too much, and the evidence appears of the possible presence of a RGB clump.

To better probe the cluster population we show in the lower left panel the stars enclosed within 1 arcmin from the cluster center. Here we see a nice MS, although significantly wide, and a well populated RGB clump. This is confirmed also by the CMD in the lower right panel, which comprises the same area as in the previous panel, and it is meant to represent the field stars population. In this CMD there is no clump at all. The cluster TO is located at \( V = 20.0 \), \( (V-I) = 1.8 \), while the clump is centered at \( V=18.2 \), \( (V-I)=2.4 \). The width of the MS is much probably not due to photometric errors (see Fig. 5, upper panel) which at \( V \approx 22 \) amounts at less than 0.1 mag in color. Therefore we suggest the MS is that wide due to other two possible reasons, which however we are not possible to quantify with the present data: a binary population and some differential reddening across the cluster.

In conclusion Saurer B exhibits all the features of an intermediate age open cluster (Carraro et al. 1999), and resembles very much the CMD of clusters like NGC 2158 (Carraro et al. 2002) and NGC 7789 (Girardi et al. 2000).

4.3 Basic parameters

We derive Saurer B fundamental parameters in the same way as for Saurer A. In Fig. 13 we plot all the stars lying within 1 arcmin from the adopted cluster center, and we show the best fit isochrone solution. Again we use a Z=0.008 isochrone (solid line), but for the age of 1.8 Gyr, which nicely fits both the TO region and the RGB clump. The fit has been obtained by shifting the isochrone by \( E(V-I) \approx 1.38 \) and \( m-M \approx 17.4 \), and the corrected distance modulus turns out to be \( m-M = 14.1 \).

In order to derive an estimate of the cluster metal content, also in this case we tried a fit with a solar metallicity isochrone (dashed line), and find an age of 2.2 Gyr, a reddening \( E(V-I) \approx 1.30 \), an apparent distance modulus \( m-M \approx 17.2 \), and corrected distance modulus turns out to be \( m-M = 14.08 \).

The quality of the CMD - in particular the region of the TO is probably still affected by some contamination - does not allow us to firmly establish the metallicity of the clusters and, indeed, the derived parameters are pretty similar. In this case, however, the cluster clump is clearly visible, and placed at \( V=18.2 \). Therefore we derive (Girardi & Salaris 2001) that for an age of 1.8 Gyr and a metallicity of \( Z=0.008 \), the absolute clump magnitude is \( V = 0.542 \), and therefore \( m-M = 17.7 \). In the case of solar abundance, the clump magnitude at 2.2 Gyr is \( V = 0.578 \), hence \( m-M = 17.6 \). Also with this method we basically obtain the same distance modulus, stressing again our inability to discriminate between different metallicity models.

As a consequence of these outcomes, Saurer B is placed 6.6 kpc far from the Sun, and its rectangular coordinates are: \( X = 9.8 \), \( Y = -6.5 \) and \( Z = -0.1 \) kpc, respectively.

To summarize, with respect to the study of FB02, we obtain a much larger distance from the Sun, and a significantly
younger age, a result which confirms the trend that the MAI predicts systematically older ages.

5 THE OPEN CLUSTER SAURER C

5.1 Cluster radius

Saurer C appears as a faint concentration of stars in a very rich Galactic field (see Fig. 3). In order to achieve an estimate of the cluster radius, we performed star counts by using our CCD data (4500 stars). We derived the surface stellar density by performing star counts in concentric rings half an arcmin in size around the visual cluster center, and then by dividing by their respective surfaces. The results are shown in Fig. 14. In this case we find an over-density of faint stars up to a radius of $\approx 2$ arcmin, while the bright stars profile keeps flat, showing that the cluster does not contain a significant amount of bright stars. By combining together the shape of the density profile and the appearance of the cluster in Fig. 3, we suggest that the cluster radius is around 2 arcmin.

5.2 The Color-Magnitude Diagram

In Fig. 15 we present several CMDs of Saurer C as a function of the distance from the cluster center. In the upper left panel the CMD for all the detected stars is shown. Here there is no cluster appearance and the CMD is dominated by the Galactic disk field stars population. If we consider only the stars located inside the cluster radius (upper right panel), Fig. 15. Left upper panel: CMD of Saurer C for all the detected stars. Right upper panel: CMD of Saurer C for all the stars within the cluster radius. Left lower panel: CMD of Saurer C for all the stars within 1.0 arcmin from the cluster center. Right lower panel: CMD of the stars outside the cluster radius, in an area equal to that one in the previous panel.
The open clusters Saurer A, B and C

Table 3. Basic data of the observed objects.

| Name    | Radius (arcmin) | $E(V-I)$ | $E(B-V)$ | $(m-M)_0$ | $X$ (kpc) | $Y$ (kpc) | $Z$ (kpc) | Age (Gyr) |
|---------|-----------------|----------|----------|-----------|-----------|-----------|-----------|-----------|
| Saurer A| 1.3             | 0.18     | 0.14     | 15.6      | 19.3      | -7.4      | 1.6       | 5.0±1.0   |
| Saurer B| 1.5             | 1.30-1.38| 1.05-1.10| 14.1      | 9.8       | -6.6      | -0.1      | 1.8-2.2   |
| Saurer C| 2.0             | 0.98     | 0.76     | 14.9      | 11.0      | -9.3      | 0.5       | ≈2.0      |

Figure 14. Star counts in the region of Saurer C as a function of the V magnitude.

Figure 16. Saurer C star within 1 arcmin from the cluster center in the V vs. $V-I$ diagram, as compared to Girardi et al. (2000) isochrone of age $2.0 \times 10^9$ yr (solid line), for the metallicity $Z = 0.008$. A distance modulus of $(m-M)_0 = 14.90$ mag, and a colour excess of $E(V-I) = 0.98$ mag, have been derived.

5.3 Basic parameters

Although the field stars contamination is very severe in the field of Saurer C, we still tried to find an isochrone solution, which of course has to be considered preliminary. The result is shown in Fig. 16, where we plot all the stars within 1 arcmin from the cluster radius. The fit has been obtained by shifting the isochrone by $E(V-I) = 0.98$ and $(m-M_V) = 17.2$, and the corrected distance modulus turns out to be $(m-M_V)_0 = 14.9$. Since the clump is placed at $V = 18.0$, we derive (Girardi & Salaris 2001) that for an age of 1.8 Gyrs and a metallicity of $Z = 0.008$, the absolute clump magnitude is $V = 0.540$, and therefore $(m-M_V) = 17.46$, in fine agreement with that derived from the isochrone fitting. As a consequence, Saurer C is placed 9.6 kpc far from the Sun, and its rectangular coordinates are: $X = 11.0$, $Y = -9.3$ and $Z = 0.5$ kpc, respectively.

6 CONCLUSIONS

We have presented deep CCD $V I$ photometry study of the old open clusters Saurer A, B and C. The CMDs we derive allow us to constrain quite well the cluster basic parameters, which are listed in Table 3. In summary, we find that:

- Saurer A is an M 67 like old open cluster and it is the most distant open cluster to date; it would be of extreme interest to have a spectroscopic confirmation of its metal abundance. RGB stars at $16 \leq V \leq 18$ are indeed easily affordable with present day 8m class telescopes;
- Saurer B turns out to be a very reddened NGC 2158 like, intermediate-age open cluster;
- Saurer C is as well an intermediate-age open cluster, but it remains a very difficult object due to the heavy field stars contamination toward its direction.

ACKNOWLEDGEMENTS

We are pleased to thank John Willis for his kind introduction at ESO NTT, and for useful suggestions during the reduction of the data presented in this paper. This study has been financed by the Italian Ministry of University, Scientific Research and Technology (MURST) and the Italian Space Agency (ASI), and made use of Simbad and WEBDA databases.

REFERENCES

Bragaglia, A., Tosi M., Marconi G., Carretta E., 2001, in The Evolution of the Milky Way: stars versus clusters, Kluwer Academic Publishers, ISBN 0-7923-6679-4, p.281
Carraro G., Chiosi C., 1994, A&A 287, 761
Carraro G., Girardi L., Chiosi C., 1999, MNRAS 309, 430
Carraro G., Ng Y.K., Portinari L., 1998, MNRAS 296, 1045
Carraro G., Girardi L., Marigo P., 2002, MNRAS 332, 705
Dean J.F., Warren P.R., Cousins A.W.J., 1978, MNRAS 183, 569
Dias W.S., Alessi B.S., Moitinho A., Lepine J.R.D., 2002, A&A 389, 871
Friel E.D., 1995, ARA&A 33, 381
Frinchaboy P.M., Phelps R.L., 2002, AJ 123, 2552
Girardi L., Bressan A., Bertelli G., Chiosi C., 2000, A&AS 141, 371
Girardi L., Mermilliod J.-C., Carraro G., 2000, A&A 354, 892
Girardi L., Salaris M., 2001, MNRAS 323, 109
Janes K.A., Phelps R.L., 1994, AJ 108, 1773
Landolt A.U., 1992, AJ 104, 340
Stetson P.B., 1987, PASP 99, 191