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Colour Magnitude Diagrams of the moderately metal-rich globular clusters NGC 6569 and Palomar 11*

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Abstract. For the first time Colour-Magnitude Diagrams are presented for NGC 6569 and Palomar 11. NGC 6569 is a rather concentrated cluster whereas Palomar 11 is loose and sparsely populated. Cluster parameters are derived from V and I photometry. These are red Horizontal Branch globular clusters, with metallicities comparable to that of 47 Tucanae. We derive a reddening $E(B-V) \approx 0.53$ and a distance from the Sun $d_\odot \approx 9.8$ kpc for NGC 6569, and $E(B-V) \approx 0.35$ and $d_\odot \approx 13.2$ kpc for Palomar 11. NGC 6569 is located in the bulge, while Palomar 11, despite its rather high metallicity, is in the inner halo, a rare case similar to that of 47 Tucanae.

Key words. Galaxy: globular clusters: individual: NGC 6569, Palomar 11 – stars: Hertzsprung-Russell diagram

1. Introduction

CCD photometric data for globular clusters within 20° × 20° around the Galactic center were recently discussed in terms of Horizontal Branch (HB) morphology by Barbuy et al. (1999). No Colour Magnitude Diagram (CMD) is available in the literature for NGC 6569. NGC 6569 is projected close to the border of the central 5° region, which was previously discussed by Barbuy et al. (1998). On the other hand, Palomar 11 is projected slightly outside the 20° × 20° region.

NGC 6569, also named GCl-91, ESO 456-SC77, is located in Sagittarius at $\alpha_{2000} = 18^{\rm h}13^{\rm m}38.9^{\rm s}$, $\delta_{2000} = -31°49'35''$ ($l = 0.48°$, $b = -6.68°$).

NGC 6569 is a rather compact cluster with concentration parameter $c = 1.27$, tidal radius $r_{\rm t} = 6.9'$, core radius $r_{\rm c} = 0.37'$ and half light radius $r_{\rm h} = 0.8'$ (Trager et al. 1995).

Zinn (1980, 1985) obtained, from integrated photometry, [Fe/H] = −0.82/−0.86 and $E(B-V) = 0.55$. From integrated DDO photometry, Bica & Pastoriza (1983) obtained [Fe/H] = −0.76 and $E(B-V) = 0.59$. The compilations by Webbink (1985) and Harris (1996, hereafter H96, as updated in http://physun.physics.mcmaster.ca/Globular.html), report [M/H] = −1.01, $E(B-V) = 0.55$, $V_{\rm HB} = 17.1$, $d_\odot = 8.9$ kpc, and [Fe/H] = −0.86, $E(B-V) = 0.56$, $V_{\rm HB} = 17.1$, $d_\odot = 8.7$ kpc, respectively.

Rosino (1962) found 6 variable stars within the cluster tidal radius. Hazen-Liller (1984, 1985) published a list of standard stars and carried out photometry for 23 variable stars within the tidal radius of NGC 6569. From 8 probable RR Lyrae members she derived a distance from the Sun $d_\odot = 7.9$ kpc.

Palomar 11, also named GCl-114, is located in Aquila at $\alpha_{2000} = 19^{\rm h}45^{\rm m}14.4^{\rm s}$, $\delta_{2000} = -08°00'26''$ ($l = 31.81°$, $b = -15.58°$).

Two unpublished CMDs of Palomar 11 were reported in literature abstracts, from which the authors derived cluster properties. Cudworth & Schommer (1984) obtained from a BV CMD $V_{\rm HB} = 17.3$, $E(B-V) = 0.34$ and $d_\odot \approx 12.9$ kpc. Cersosimo et al. (1993) derived from BVI CMDs $V_{\rm HB} = 17.35$ and [Fe/H] = −0.23. Both reports describe a red HB. Zinn (1985) gives [Fe/H] = −0.7 and $E(B-V) = 0.35$. Webbink (1985) and H96 list [M/H] = −0.92, $E(B-V) = 0.34$, $V_{\rm HB} = 17.38$, $d_\odot = 13.8$ kpc, and [Fe/H] = −0.39, $E(B-V) = 0.34$, $V_{\rm HB} = 17.35$, $d_\odot = 12.9$ kpc, respectively.

Rosino & Ortolani (1985) reported that no variables were detected in this cluster.

Palomar 11 has a loose structure with $c = 0.69$. The tidal radius is $r_{\rm t} = 9.8'$, the core radius $r_{\rm c} = 2'$ and the half light radius $r_{\rm h} = 1.5'$ (Trager et al. 1995).

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In terms of absolute magnitude NGC 6569 and Palomar 11 have $M_V = -7.72$ and -6.63 respectively (van den Bergh 1996), so that NGC 6569 has a typical average luminosity of a globular cluster in the Galaxy, while Palomar 11 is underluminous.

In Sect. 2 the observations and reductions are presented. In Sects. 3 and 4 we analyse the Colour-Magnitude Diagrams of NGC 6569 and Palomar 11, respectively. A summary is given in Sect. 5.

2. Observations

NGC 6569 was observed on the night of 2000 March 6, with the 1.5 m Danish telescope at ESO La Silla. The telescope was equipped with the DFOSC camera and a Loral/Lesser CCD detector C1W7 with 2052× 2052 pixels. The pixel size of this CCD is 15 μm, corresponding to 0.39″ on the sky, providing a full field of 13′×13′. Palomar 11 was observed on the night of 2000 March 7, using the same equipment. Both nights were photometric. The log of observations is presented in Table 1. In Fig. 1 is shown a 4 min full field V image of NGC 6569. The cluster appears compact and populous, prominent against the background. Figure 2 shows a 1500×1500 pixel central extraction from a V 60 s exposure of Palomar 11. This is a very poorly populated, sparse cluster, typical of the Palomar clusters. Daophot II and Allstar have been used to extract the instrumental magnitudes. The calibration has been carried out using Landolt (1983, 1992) standard stars observed during the same nights. The derived calibration equations for the night of March 6 are:

$$B = 26.40 + 0.1\ (B - V) + b$$

$$V = 26.46 + 0.01\ (V - I) + v$$

$$I = 24.61 - 0.01\ (V - I) + i$$

reduced to 15 s and to 1.15 airmasses in B, 10 s in V, and 5 s in I. These exposure times correspond to those of the standards. The constant in V for the night of March 7 is 26.45 and in I it is the same as the previous night. The zero point and slope errors of the equations are about ±0.015. However, the calibration error is largely dominated by crowding effects in the determination of the aperture corrections of the cluster stars. This error is estimated to be about ±0.03 mag. The CCD shutter time uncertainty (around 0.1–0.3 s) related to the short exposures used for the standard stars leads to an additional 2–3 percent error, which is propagated to the calibration of the longer exposure cluster frames. Thus the final zero point uncertainty of our photometry is estimated to be ±0.05. The atmospheric extinction was corrected using the standard La Silla coefficients ($C_V = 0.13$ and $C_I = 0.1$ mag/airmass). The adoption of these standard values is justified because the airmass difference between the standard stars and the clusters was within 0.1 airmass, which gives a correction of about 0.01 magnitudes.

Table 1. Log of observations.

Target	Filter	Date	Exp. (sec.)	Seeing (″)
NGC 6569	I	06.03.00	10	1.1
	V	″	60	″
	I	″	40	1.2
	V	″	240	1.25
	B	″	90	1.2
Pal 11	V	07.03.00	60	1.3
	I	″	60	1.3

We compared the present B and V photometry of NGC 6569 with the photoelectric B and V sequence published by Hazen-Liller (1984), and with the secondary stars from the B photographic photometry by Hazen-Liller (1985). The difference Hazen-Liller vs. present CCD data for 5 photoelectric standards is $\Delta V = 0.02 \pm 0.01$ mag and $\Delta B = -0.017 \pm 0.02$ mag. There is good agreement, considering the possible sources of systematic errors discussed above. However, the comparison with her secondary sequence, which was derived from the Racine's prism technique for photographic plates, lead to a noticeable difference with our B photometry, increasing systematically with the magnitude. It starts with about $\Delta B = -0.07$ in the range $14.5 < B < 15.5$, reaching -0.3 mag at $B = 17$. If the difference is due to calibration problems on the photographic plates, it is easy to explain why Hazen-Liller (1985) gave systematically brighter RR Lyrae stars than in the present photometry (see Sect. 3.1), and a shorter distance for the cluster.

3. NGC 6569

3.1. Colour-Magnitude Diagrams

In Fig. 3 we show the V vs. $V - I$ CMD of the field surrounding NGC 6569, corresponding to an extraction of radius $r > 2.9'$ ($r > 450$ pixels). It is a typical bulge field, very similar to that of the neighbouring globular cluster NGC 6558 (Rich et al. 1998). Both clusters are located in the $-6°$ window on the minor axis. The Red Giant Branch (RGB) is very extended ($\Delta V - I \approx 5$ mags) and shows the turn-over characteristic of metal-rich populations (e.g. Ortolani et al. 1990). The blue sequence corresponds to a disk Main Sequence (MS) contamination, since the cluster is located at a low Galactic latitude.

Figure 4 shows the V vs. $V - I$ CMD corresponding to an extraction of $r < 1'$ ($r < 150$ pixels), thus comparable to the cluster half light radius (Trager et al. 1995). The cluster sequences are rather broad owing to differential reddening. The mean locus of the metal-rich ([Fe/H] = -0.7, Zinn & West 1984) globular cluster 47 Tuc, as derived from the photometry of Desidera & Ortolani (1997), also published in Barbuy et al. (1999), is superimposed on

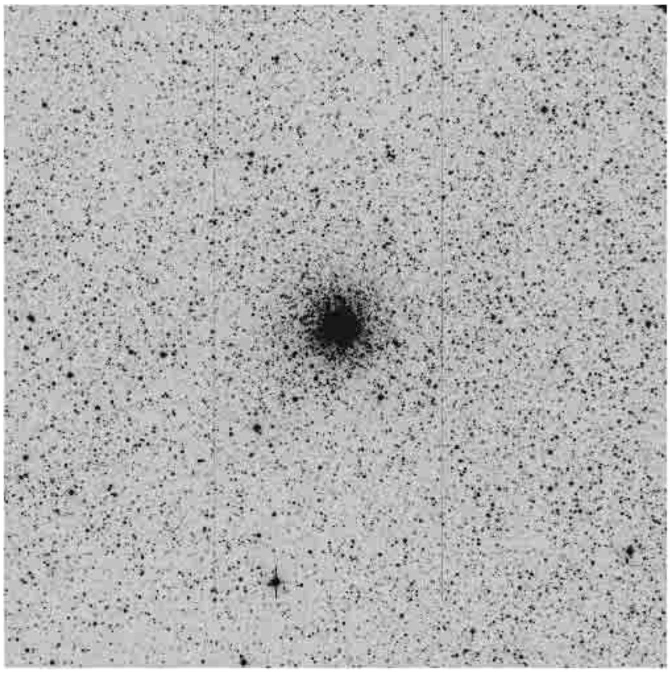

Fig. 1. NGC 6569: V image (240 s) for full field. Dimensions are $13' \times 13'$ (2000×2000 pixels). North is at the top and east to the left.

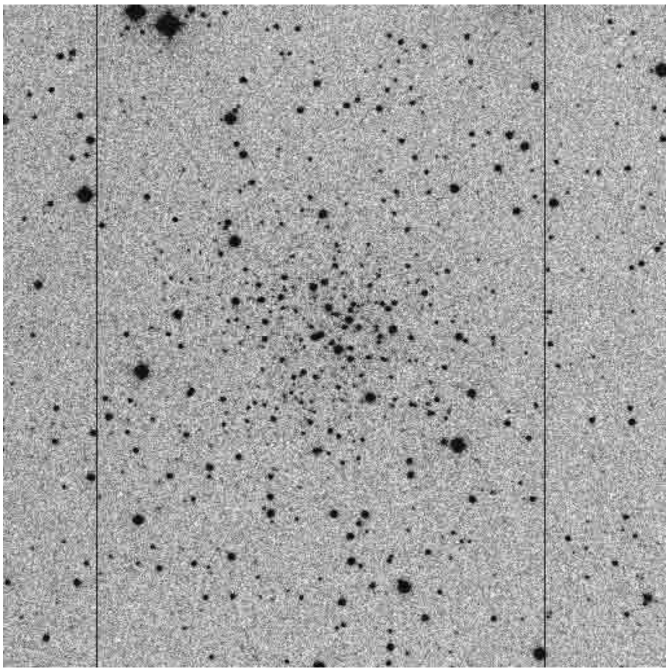

Fig. 2. Palomar 11: V 60 s image with dimensions $6.6' \times 6.6'$ (1020×1020 pixels). North is at the top and east to the left.

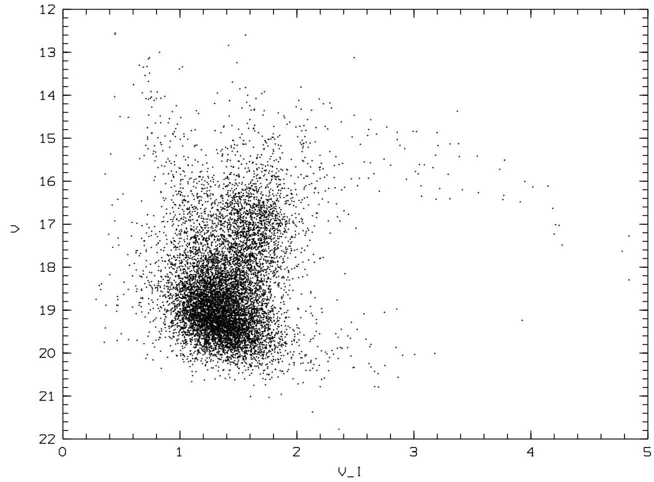

Fig. 3. Field of NGC 6569: V vs. $V - I$ CMD for $r > 2.9'$ ($r > 450$ pixels).

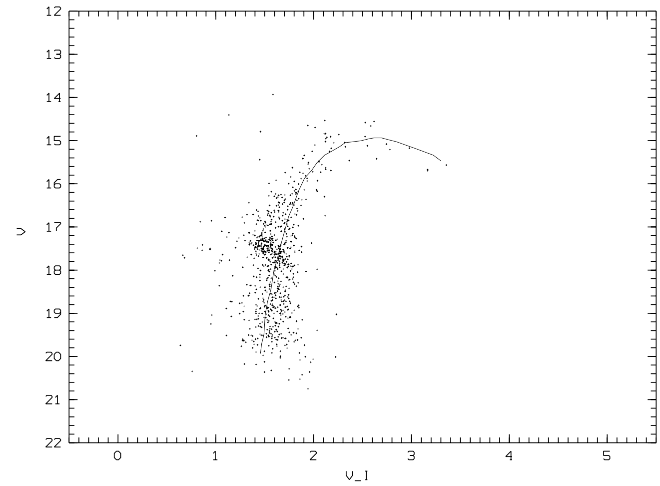

Fig. 4. NGC 6569: V vs. $V - I$ CMD extraction for $r < 1'$ ($r < 150$ pixels). The mean locus of 47 Tuc, derived from the 47 Tuc CMD given in Barbuy et al. (1999), is superimposed.

the cluster CMD. The cluster is clearly dominated by a red HB, but some bluer HB stars may be present.

NGC 6569 is very rich in variable stars: 16 variables reported by Hazen-Liller (1985) within $r < 8'$ have been identified in our photometry. These are the variable stars in the area except V18 and V21 which are in too crowded a region for a reliable identification. These variables are identified in the V vs. $V - I$ CMD of Fig. 5a (expanded from the extraction $r < 150$ pixels, Fig. 4). We show in Fig. 5b the distribution of the RR Lyrae candidates and the two Long Period variables in the V vs. $B - V$ CMD. Eight of them (V1, V2, V8, V14, V17, V20, V22, V23) have similar magnitudes and colours with an average $V = 17.52 \pm 0.04$ and $V - I = 1.17 \pm 0.03$, with a blue limit at $V - I = 1.02$ and a red one at $V - I = 1.27$. Assuming the derived reddening of $E(V-I) = 0.72 \pm 0.05$ we obtain an average corrected colour $V - I = 0.55 \pm 0.05$, in agreement with the expected value for the RR Lyrae of a relatively metal-rich cluster. From the BV photometry we obtained an average colour of $B - V = 0.81$, corresponding to a reddening corrected value $B - V_{\rm o} \approx 0.25$, within the instability strip of the RR Lyrae stars. The small dispersion of their V magnitudes seems to confirm the membership of these variables. Hazen-Liller's mean value $V = 17.52$ is also compatible with the present mean value of the HB level $V = 17.50 \pm 0.1$ (Sect. 3.2). However, $<B>$ for these RR Lyrae is 18.36 ± 0.035 in the present photometry, while Hazen-Liller gives $<B> = 17.95$. The difference cannot be accounted for only by a statistical median vs. mean value difference and it is more likely due to a linearity deviation in the calibration of the photographic plates as discussed in Sect. 2.

Two additional RR Lyrae (V11 and V5), represented also by open circles in Fig. 5a, lie far from the average, both in colour and luminosity. V5 is too red and too bright to be a member, but it might be affected by crowding and possibly misidentified. V11, which is at $r > 2'$ from the cluster center, is too bright ($V = 17.1$) and too blue compared to the members. This appears also in Hazen-Liller's study where it was found to be 0.2 mag brighter in B. Only a peculiar lower reddening in the line of sight of this star could make it compatible with the other RR Lyrae stars of the cluster. We also confirm that V4 and V12, indicated as open squares in Fig. 5a, are likely non-members. The two suspected eclipsing variables V9 and V10 (open triangles in Fig. 5a) are definitely much brighter than the RR Lyrae stars. We have counted the stars in the RR Lyrae gap, at $0.9 < V - I < 1.2$ and $17 < V < 18$. There are 10 stars in the cluster area within a radius of $r < 150$ pixels centered on the cluster. In 4 fields of equivalent area, an average of 4 stars are found. This means that the probability that the RR Lyrae belong to the cluster is around 50%.

V3 and V16 are located in the expected region for red variables in the cluster CMD. V3 is very red and likely a red semiregular or a long period variable. Hazen-Liller indicates V16 as a possible population II Cepheid in the cluster. In our photometry V16 is quite crowded, with $V = 14.66$ and $V - I = 2.58$, located in the upper envelope of the red giant. While the CMD locus is compatible with membership, further observations are required to check whether it is a rare case of a population II Cepheid in a relatively metal rich globular cluster, or, more likely, another red semiregular or long period variable.

Hazen-Liller (1985), based on the presence of several RR Lyrae and a Cepheid, predicted a blue HB for the cluster. However the CMDs (Figs. 4, 5a,b) have shown a dominant red HB.

3.2. Cluster parameters

3.2.1. Metallicity

In Fig. 4 the mean locus of the globular cluster 47 Tuc is overplotted. The RGB and the HB are fitted by the mean locus of 47 Tuc, suggesting a comparable metallicity. A few other globular clusters have metallicities at the low end of the metal-rich class, such as NGC 6712 of $[Fe/H] \approx -1.0$ (Ortolani et al. 2000) and NGC 6171 $[Fe/H] \approx -1.04$ (Ferraro et al. 1991; H96). These two clusters differ from NGC 6569 in the sense that they present a clear blue HB component, besides the dominant red HB. On the other hand, with respect to 47 Tuc, NGC 6569 has a significant population of RR Lyrae (Sect. 3.1). Therefore NGC 6569 should be somewhat more metal-rich than these two clusters, around $[Fe/H] \approx -0.9$.

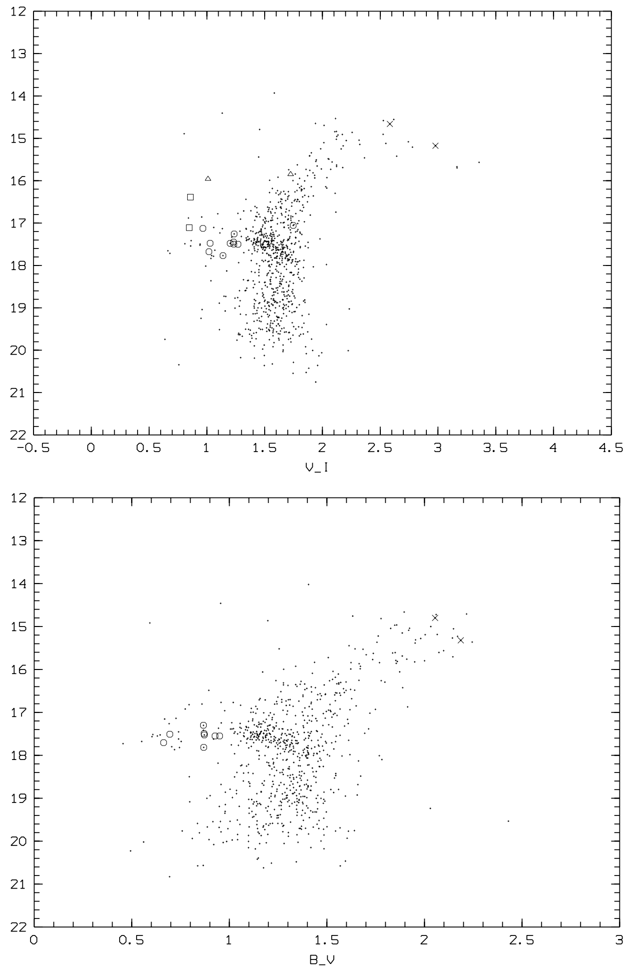

Fig. 5. NGC 6569 variables identified in a CMD extraction of $r < 1'$ ($r < 150$ pixels). **a)** V vs. $V - I$ with symbols: open circles are cluster RR Lyrae candidates; open squares are field RR Lyrae candidates; open triangles are eclipsing variables; crosses are red variables. **b)** V vs. $B - V$ with same symbols as in **a)**.

In terms of CMD morphology and metallicity, the clusters NGC 6171, NGC 6569 and NGC 6712 have a dominant red HB, and should be the lower end of the high metallicity regime. A class of clusters slightly less metal-rich than these, are NGC 6540 (Bica et al. 1994), NGC 6558 (Rich et al. 1998), NGC 6256 and NGC 6717 (Ortolani et al. 1999) which do not present a red HB, but have $[Fe/H] \approx -1.2$. They are located in the bulge often showing post-core collapse structure, and a blue tail HB. This class would correspond to the upper end of the intermediate metallicity clusters.

3.3. Cluster reddening and distance

The HB is located at $V_{\rm HB} = 17.50 \pm 0.1$ and the colour of the RGB at the HB level is $V - I = 1.70 \pm 0.05$. The difference with respect to a best fit with 47 Tuc is $\Delta(V - I)_{\rm (NGC\ 6569-47\ Tuc)} = 0.65$, and since $E(V - I) = 0.05$ for 47 Tuc, this implies a reddening of $E(V - I) = 0.70$. With $E(V - I)/E(B - V) = 1.33$ there results $E(B - V) = 0.53$

for NGC 6569. The cluster is projected towards the dark nebula Barnard 305 (Barnard 1927), which explains the relatively high reddening in this direction, and implying that the dust cloud is foreground to the cluster.

Adopting $R = 3.1$ we get $A_V = 1.64$, and using $M_V^{\rm HB} = 0.85$ (Buonanno et al. 1989), we get $(m-M)_{\rm o} = 14.96$, and the distance to the Sun $d_\odot = 9.8 \pm 1.0$ kpc for NGC 6569. Assuming the distance of the Sun to the Galactic center to be $R_\odot = 8.0$ kpc (Reid 1993), the Galactocentric coordinates are $X = 1.7$ kpc ($X > 0$ is on the other side of the Galaxy), $Y = 0.1$ kpc and $Z = -1.0$ kpc. The distance from the Galactic center is $R_{\rm GC} = 2.0$ kpc.

NGC 6569 is thus located in the bulge. We also conclude that is does not form a physical pair with NGC 6558 which is closer at $d_\odot = 6.3$ kpc (Rich et al. 1998).

4. Palomar 11

4.1. Colour-Magnitude Diagrams

In Fig. 6 we show the V vs. $V-I$ CMD of the whole frame, centered on Palomar 11. Since this field is located at a higher Galactic latitute ($b = -15.57°$) it is considerably less populated than lower latitude fields such as that of NGC 6569 (Fig. 3). The cluster stars are barely seen, except for the clump located at $V \approx 17.4$ and $V-I \approx 1.4$. A blue disk MS is seen.

Figures 7a,b show the V vs. $V-I$ CMD corresponding to an extraction of $r < 1.2'$ ($r < 180$ pixels). The red clump is clear, the RGB is underpopulated but can be seen, and the subgiant branch is well populated. Disk contamination is still present and does not allow us to identify blue HB stars, if there are any. The major conclusion is that it has a dominant red HB, as previously suggested in the literature. Figure 7b shows the same stars as in Fig. 7a with the mean locus of the template globular cluster 47 Tuc overimposed. In order to estimate the number density of field stars in this extraction, we counted the number of stars within radius $r < 180$ pixels and $V < 19$ centered on the cluster, which is 82 stars. The equivalent field contains 19 stars. This means that, on average, the contamination by field stars in the cluster area is around 20%.

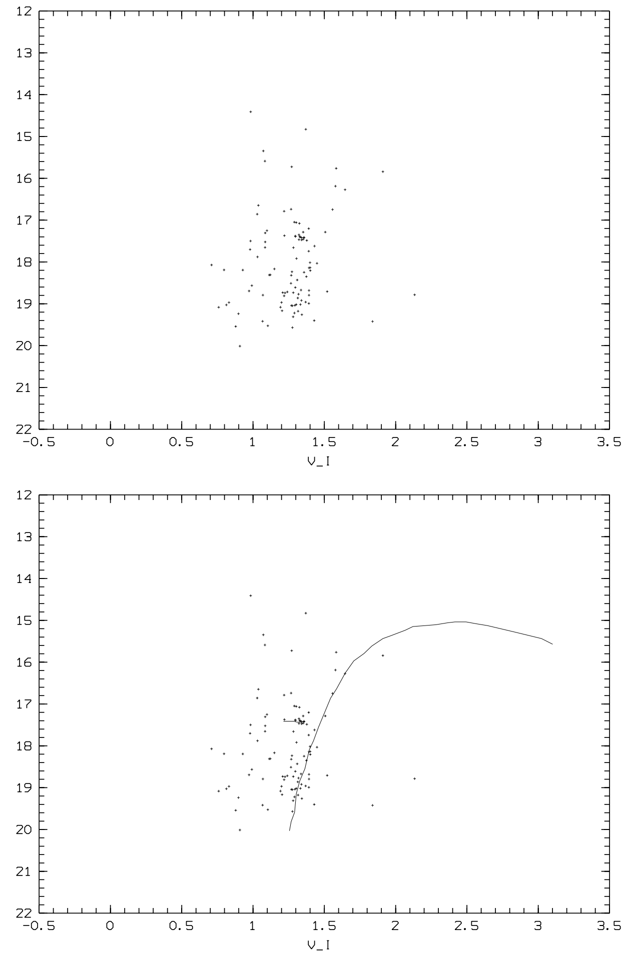

Fig. 7. Palomar 11: **a)** V vs. $V-I$ CMD of an extraction of $r < 1.2'$ ($r < 180$ pixels); **b)** same as **a)** with mean locus of 47 Tuc superimposed.

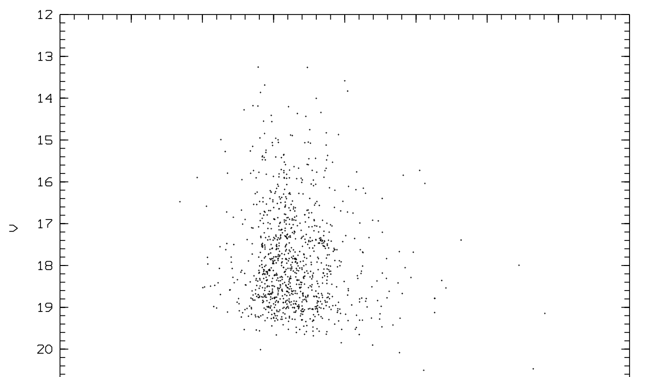

Fig. 6. Field of Palomar 11: V vs. $V-I$ CMD of full field including the cluster, with dimensions $13' \times 13'$ (2000×2000 pixels).

It would be important to obtain CMDs of Palomar 11 which attain the cluster MS. A deep luminosity function might reveal depletion, as with other Palomar type clusters, e.g. E3 (McClure et al. 1985), NGC6717 (Ortolani et al. 1999) and ESO452-SC11 (Bica et al. 1999). Such poorly populated globular clusters appear to be in evolved dynamical stages, possibly dissolving.

4.2. Metallicity

The RGB and in particular the HB are well fitted by the mean locus of 47 Tuc. The separation between the RGB and the red HB is our main constraint in estimating its metallicity, since the RGB is underpopulated. The location of the HB relative to the RGB matches well that of 47 Tuc, suggesting that they have essentially the same metallicity. Thus we adopt [Fe/H] = -0.7 for Palomar 11.

4.3. Cluster reddening and distance

The HB is located at $V_{\rm HB} = 17.40 \pm 0.1$ and the colour of the RGB at the HB level is $V - I = 1.47 \pm 0.08$. The difference with respect to a best fit with 47 Tuc is $\Delta(V - I)$(Palomar 11–47 Tuc) = 0.42, and since $E(V - I) = 0.05$ for 47 Tuc, this implies a reddening of $E(V-I) = 0.47$. With $E(V-I)/E(B-V) = 1.33$ there results $E(B - V) = 0.35$ for Palomar 11. Adopting $R = 3.1$ we get $A_V = 1.09$, and using $M_V^{\rm HB} = 0.7$ (Buonanno et al. 1989), there results $(m - M)_{\rm o} = 15.61$, and the distance to the Sun $d_\odot = 13.2 \pm 1.0$ kpc for Palomar 11.

The Galactocentric coordinates are $X = 3.2$ kpc, $Y = 6.1$ kpc and $Z = -3.2$ kpc. The distance from the Galactic center is $R_{\rm GC} = 7.6$ kpc. Note that 47 Tuc is located at the Galactocentric distance $R_{\rm GC} = 7.7$ kpc and distance from the plane $Z = -3.2$ as given in H96. Both values are comparable to those of Palomar 11, which turns out to be another metal-rich cluster located in the inner halo.

5. Conclusions

We provide the first Colour-Magnitude Diagrams for NGC 6569 and Palomar 11, and we were able to derive their properties.

Both clusters have red Horizontal Branches, and NGC 6569 appears to have RR Lyrae as well. For NGC 6569 we estimate a metallicity of [Fe/H] ≈ -0.9, at the lower end of the metal-rich family of globular clusters. For Palomar 11 [Fe/H] ≈ -0.7 is estimated.

NGC 6569 presents a reddening of $E(B - V) = 0.53$ and a distance from the Galactic center of $R_{\rm GC} = 2.0$ kpc and a distance from the Sun $d_\odot = 9.8$ kpc. Therefore although it is projected very close to NGC 6558, it is considerably more distant and they do not form a physical pair.

For Palomar 11 we derive a reddening of $E(B - V) = 0.35$ and a distance from the Galactic center of $R_{\rm GC} = 7.6$ kpc and a distance from the Sun $d_\odot = 13.2$ kpc. It is thus a metal-rich globular cluster, located outside the bulge. Its inner halo location and its metallicity makes it likely to be a rare case similar to that of 47 Tucanae.

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