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UBV photometric study and basic parameters of the southern open cluster NGC 2539[⋆,⋆⋆]

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Abstract. We present UBV photoelectric observations of 345 stars in the field of the southern open cluster NGC 2539. The analysis of these data allows to determine that 169 stars are probable members of the cluster main sequence, while 23 are possible members. The CC and CM diagrams reveal a well-defined main sequence and a populous red giant branch. We derive a reddening $E(B-V)$ = 0.06 and an apparent distance modulus $V - M_v$ = 10.60, equivalent to a distance of 1210 pc. The age, determined by fitting isochrones computed by the Geneva group with mass loss and moderate core overshooting, turns out to be 630 Myr, which places this cluster within the Hyades-age group. The isochrone for $\log t$ = 8.80 reproduces well the morphology of the upper main sequence band in the two CM diagrams, including the binary ridge. Although this isochrone also reproduces well the general shape of the observed red giant pattern, it appears to be a little too bright and too red. This fact could be probably due to the uncertainty on the exact value of the mixing-length parameter. However, mass loss during the evolution of the red giants might also partially account for their location in the HR diagram. The low contamination of the upper main sequence of the cluster CM diagrams and its populated red giant branch makes NGC 2539 a very good target for testing of theoretical models.

Key words: Galaxy: open clusters and associations: general – Galaxy: open clusters and associations: individual: NGC 2539 – stars: Hertzsprung–Russel (HR) and C-M diagrams – methods: observational

1. Introduction

NGC 2539 is an intermediate-age sparse open cluster in the southern constellation of Puppis. The existing photometric and spectroscopic data are far from being complete. Pesch (1961) published a UBV photoelectric study of 59 stars in the cluster field and classified only 19 tentative main sequence members and several yellow and red giant candidates. He estimated a reddening $E(B-V)$ = 0.10, a distance of about 1300 pc and a height above the Galactic plane of 250 pc. Later, Becker & Fenkart (1971) re-analysed Pesch's data and found a true distance modulus $V_0 - M_v$ = 10.60 which corresponds to a distance of 1130 pc, an angular diameter of 22′ and a turn-off spectral type of A0. More recently, Joshi & Sagar (1986) obtained UBV photometry of 88 stars in the region of NGC 2539 and derived the following parameters: $E(B-V)$ = 0.08, r = 1500 pc and t = 540 Myr. At the same time, we obtained DDO and Washington photoelectric photometry of 13 bright G- and K stars in the cluster field (Clariá & Lapasset 1986a, Paper I). Using photometric criteria, we found seven stars to be red giant members of NGC 2539, which was confirmed by the radial-velocity analysis of Mermilliod & Mayor (1989). We also determined the following cluster parameters: mean reddening $E(B-V)$ = 0.08 $\pm$ 0.02, distance modulus $V_0 - M_v$ = 9.8 $\pm$ 0.5 (r = 910 $\pm$210 pc) and age of (640 $\pm$ 80) Myr. This study revealed two inconsistencies: the metallicity derived from different photometric indexes were [Fe/H] = 0.2 and -0.2 respectively, and the average mass (M = 1.3 $\pm$ 0.2 $M_\odot$) of the red giant sample was too low according to theoretical models. The first problem was partially overcome when new CMT_1T_2 calibrations (Canterna et al. 1986) were applied and the abundance discrepancies were reduced. The improved metallicity of NGC 2539 red giants deduced by Clariá et al. (1989) was [Fe/H] = 0.03 $\pm$ 0.09, i.e., a "normal" solar metallicity. The "mass" problem requires an improvement of most of the fundamental cluster parameters: reddening, distance modulus and age. But, as stated in Paper I, it appears unlikey that the uncertainties of these parameters are responsible for the low masses derived. Most probably, this result is indicating that the cluster giants could indeed have suffered mass loss during their red giant phase of evolution. Similar conclusions were obtained for other intermediate-age and old open clusters by Dawson (1978), Clariá (1979, 1985), Clariá & Lapasset (1983, 1989) and others.

The present paper is an attempt to complete the photometric study of NGC 2539, with the aim of determining the main cluster parameters with improved accuracy. We report here the results obtained from photoelectric UBV observations of 345 stars brighter than about V = 15 in the cluster field. These data

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⋆ Based on observations made at Las Campanas Observatory (Chile) and at European Southern Observatory, La Silla (Chile)

⋆⋆ Table 1 is only available in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via http://cdsweb.u-strasbg.fr/Abstract.html allow the construction of well-defined colour-magnitude (CM) and colour-colour (CC) diagrams which, in turn, allow the determination of membership and fundamental characteristics of the cluster.

2. Observations

2.1. UBV photoelectric observations

The UBV measurements were carried out during an observing run with the 1.0m telescope of the European Southern Observatory (ESO) at La Silla (LS, Chile) and several runs with the 0.60m Canadian telescope of the David Dunlap Observatory located in Las Campanas Observatory (LCO). A Ga-As RCA 31034 phoptomultiplier tube was used at ESO, while an RCA 1P21 or an EMI 9658 phototube were employed at LCO. All them were cooled by dry ice and equipped with pulse-counting electronics and standard UBV filters. Mean extinction coefficients at both observatories were employed to correct for atmospheric absorption and nightly observations of about 12 E-regions standards (Cousins 1973, 1974) were used to transform to the UBV system. We found evidence of significant systematic discrepancies in the $(U-B)$ colours of stars observed at both observatories. When the $(U-B)_{\rm LS}$ measurements are plotted against $(U-B)_{\rm LCO}$, the following least-square relation is obtained from 31 stars measured at both observatories:

$$(U-B)_{\rm LCO} = 0.417(U-B)_{\rm LS} + 0.083 \tag{1}$$

Since the significant colour term in $(U-B)$ is most probably due to the presence of the moon and the comparatively low signal to noise ratios obtained with the U filter for the stars measured at LS, we corrected the $(U-B)_{\rm LS}$ values using the above equation and assigned half weight to the corrected $(U-B)_{\rm LS}$ values when averaged with the individual $(U-B)_{\rm LCO}$ values. We also corrected for the small systematic drifts in V and $(B-V)$ using the following equations:

$$\begin{aligned} V_{\rm LCO} &= 1.015V_{\rm LS} - 0.158, \\ (B-V)_{\rm LCO} &= 1.041(B-V)_{\rm LS} - 0.022, \end{aligned} \tag{2}$$

and assigned equal weight to the corrected V and $(B-V)$ values when averaged with the corresponding LCO values. In general, our internal and external errors are similar to those in previous papers (e.g., Clariá et al. 1991), i.e., less than about 0.02–0.03 mag. Thus we considered as probable variables stars having more than five times this error. These stars were previously reported as probable variables by Lapasset et al. (1991).

A total of 345 stars were measured in the field of NGC 2539, enlarging by a factor of three the number of previously observed stars. Most of the stars were observed more than once, the number of observations per star being between 1 and 5. The observed objects are essentially located inside five annular regions around the adopted cluster center. The outer radii of regions I, II, III, IV and V in Fig. 1 are 3.0, 5.2, 8.0, 10.5, and 12.8 arcmin, respectively. Some stars were also measured beyond the outer ring (region VI). The final UBV data are presented in Table 1. Nine columns in this table list successively: (1) star identification on the finding chart, the first digit indicating the ring number, (2) identification number given by Pesch (1961) or the BDA catalog (Mermilliod 1995), (3 and 4) rectangular coordinates, (5) number of independent measurements, (6) V magnitude, (7 and 8) $B-V$ and $U-B$ colours, and (9) adopted photometric membership estimates. The probable variables have also been identified in the first column of Table 1. The first 5 lines are shown here and the entire table is available only in electronic form at the CDS via anonymous ftp to cdsarc.u-strasbg.fr.

Table 1. UBV photoelectric observations of NGC 2539

No	BDA	X	Y	n	V	(B-V)	(U-B)	M
101	40	645	484	2	12.057	0.245	0.131	m
102	176	645	492	1	14.217	0.535	0.040	m
103	177	648	496	1	13.824	0.809	0.214	nm
104	41	646	510	3	12.407	0.277	0.149	m
105	117	635	520	3	11.422	0.169	0.158	m

We compare our photoelectric photometry with the two previous less extensive UBV surveys carried out by Pesch (1961) and Joshi & Sagar (1986). The agreement between Pesch's and our photometry is quite good (Fig. 2). The resulting mean differences (in the sense Pesch minus this study) for a total of 54 stars in common are ΔV = 0.002 $\pm$ 0.030, $\Delta(B-V)$ = -0.007 $\pm$ 0.021 and $\Delta(U-B)$ = 0.020 $\pm$ 0.051. The same mean differences between Joshi & Sagar's and our data for a total of 79 stars in common are 0.012 $\pm$ 0.086, -0.022 $\pm$ 0.056 and 0.028 $\pm$ 0.077, respectively. The agreement is poorer in this second case (Fig. 3). Moreover, some stars were discarded from the statistics because of large discrepancies, in most cases surely due to miss-identifications or to large photometric errors.

2.2. New radial-velocity observations

CORAVEL radial-velocity observations for 13 red giants (11 members) were published by Mermilliod & Mayor (1989). Additional observations made in 1991 and 1995 did not reveal new binaries. After Paper I was published, a few more red-giant candidates were observed from the ESO observatory at La Silla during the course of CORAVEL normal observing runs to check their membership. Table 2 presents the observations for the additional stars. The columns contain successively: the present numbers, Pesch (1961) original designation, the radial velocity and the error in [km s^{-1}], the number of measurements, the time spent by the dates and the probability P(χ^2) that the differences are due to random errors. Although the radial velocities of stars 622, 665 and P29 are within 4 km s^{-1} of the mean cluster velocity (+29.27 $\pm$ 0.14 km s^{-1}) derived by Mermilliod & Mayor (1989), they are fainter and redder than the clump and are therefore probably non-members. However, further radial-velocity observations are necessary to check for a possible duplicity. If the systemic velocity would favour their membership, their red positions could be explained by an anomalous binary evolution.

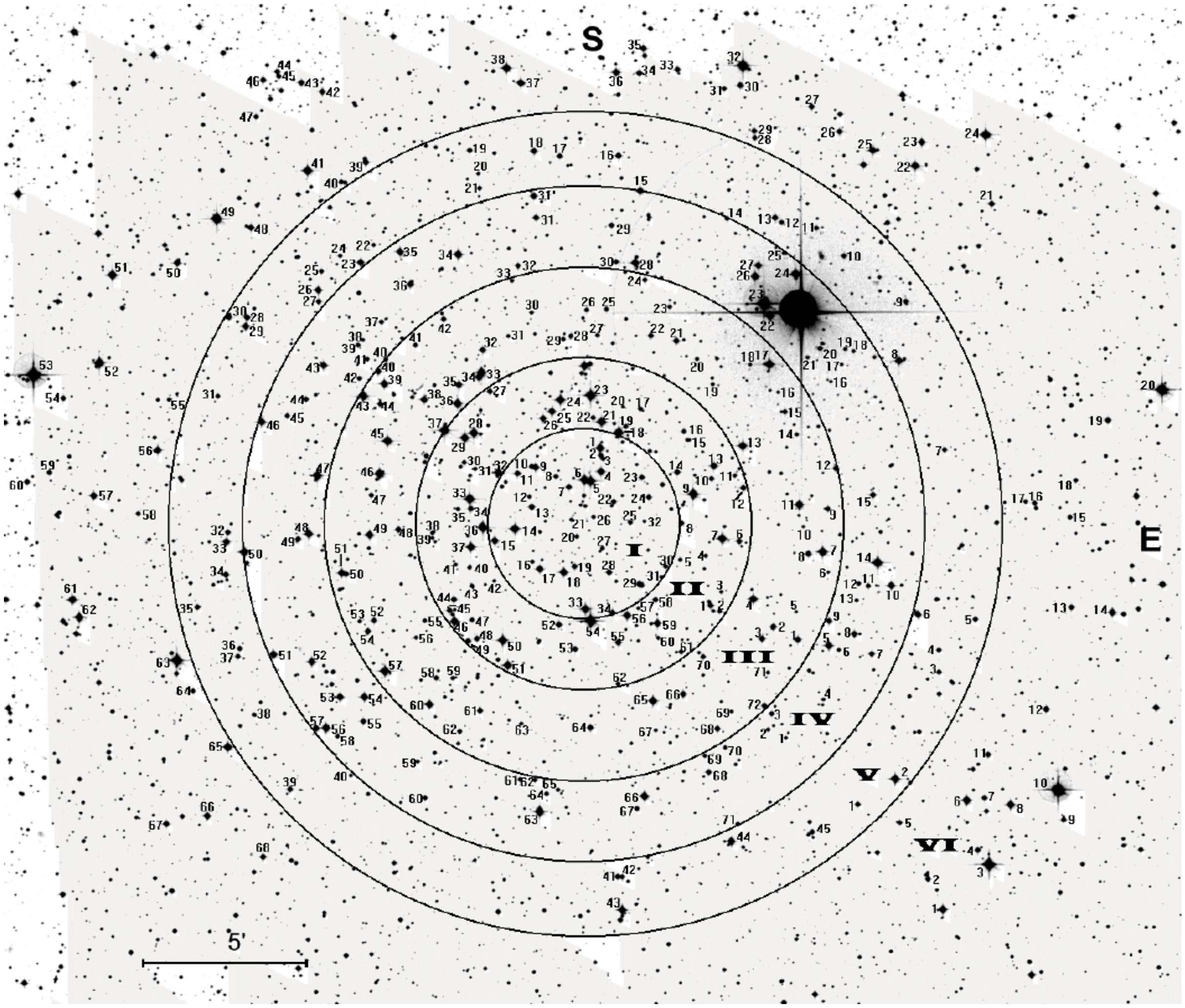

Fig. 1. Identification chart for stars in the field of NGC 2539. The outer radii of regions I, II, III, IV and V are 3.0, 5.2, 8.0, 10.5 and 12.8 ′, respectively

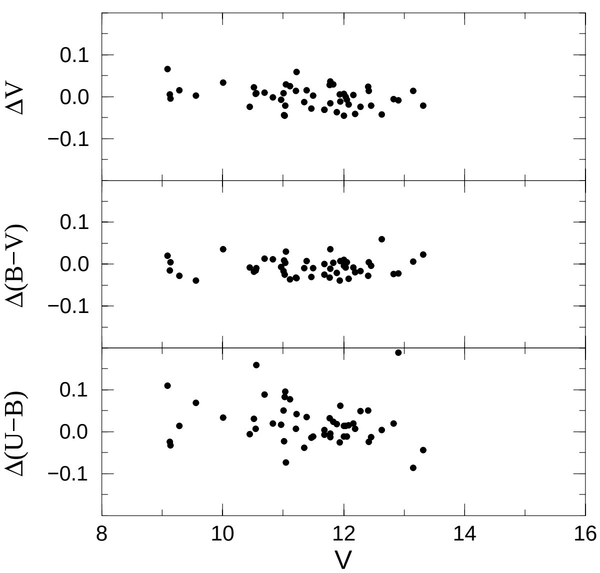

Fig. 2. Magnitude and colour difference (Pesch minus this study) versus V-magnitude

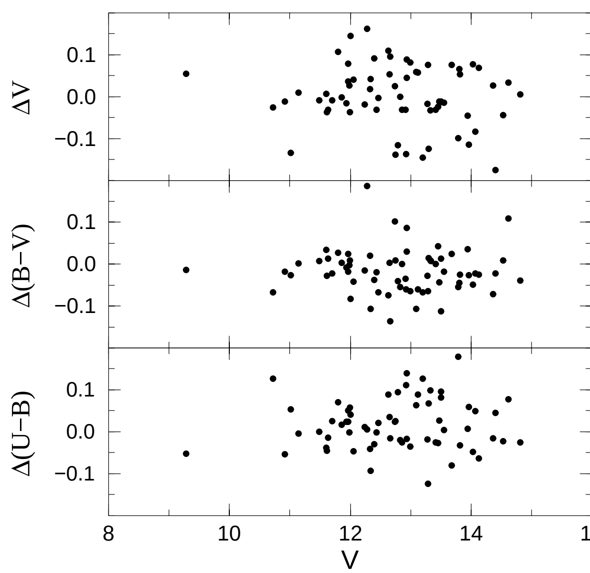

Fig. 3. Magnitude and colour difference (Joshi & Sagar minus this study) versus V-magnitude

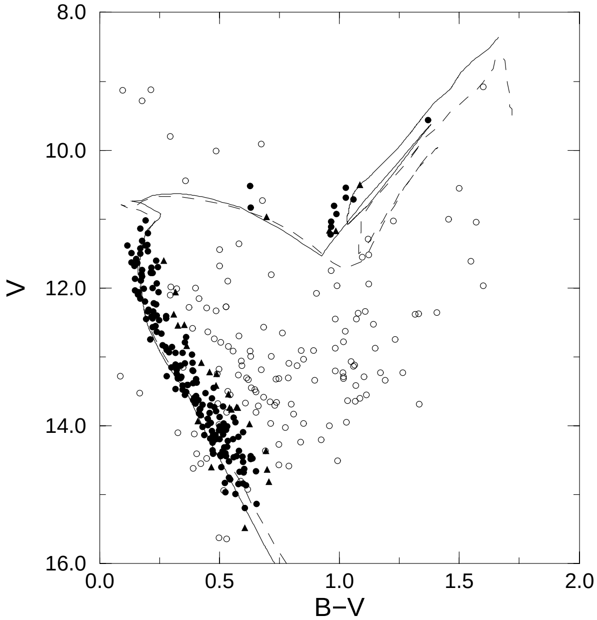

Fig. 4. The observed $(V,\, B-V)$ diagram for NGC 2539. Probable cluster members are represented by filled circles, possible members by filled triangles and non-members by open circles. Schaller et al. (1992) and Bertelli et al. (1994) isochrones, represented by solid and dashed lines respectively, have been adjusted to the observations.

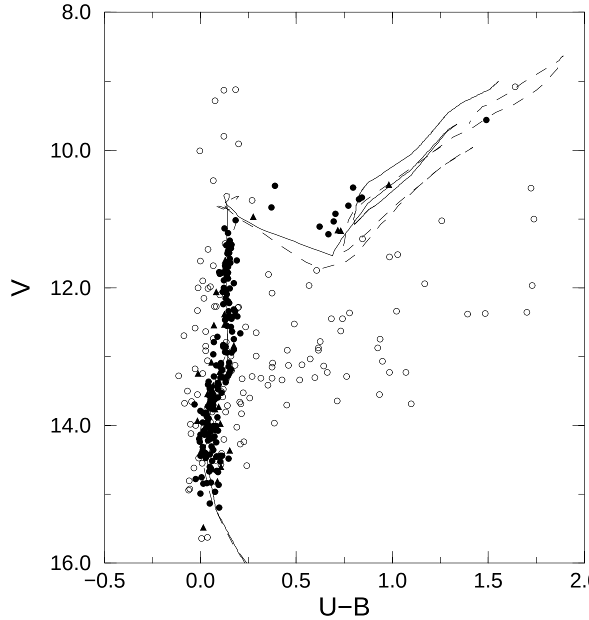

Fig. 5. The observed $(V,\, U-B)$ diagram for NGC 2539. Symbols and isochrones are as in Fig. 4.

Table 2. CORAVEL data for red giant candidates in NGC 2539

No	P	Vr	ϵ	N	Δ T	P(χ^2)	Rem
622	7	+32.15	0.35	1			nm
	15	+69.14	0.38	1			nm
651	16	+45.16	0.33	1			nm
665	22	+26.76	0.23	2	322	0.344	nm
	29	+32.53	0.34	1			nm
133	47	+110.65	0.40	1			nm

3. UBV analysis

3.1. Membership criteria

Figs. 4, 5 and 6 show the observed CM and CC diagrams constructed from the photometric data in Table 1. Membership in NGC 2539 has been determined by examining the positions of individual stars in these diagrams. Except for the red giants, cluster members were selected following the criteria described by Clariá & Lapasset (1986b), namely, by requiring the location of the stars in both CM and in the CC diagrams to correspond to the same evolutionary stage and that the location of the star in the CC diagram be close to the main sequence (MS), the maximum departure accepted being 0.10 mag. Stars classified as probable members (m), possible members (pm) and non members (nm), are represented by filled circles, filled triangles and open circles in Figs. 4, 5 and 6, respectively. We find that 169 stars are probable members of the cluster main sequence, while 23 are possible members.

Both CM diagrams reveal the presence of a reasonably broad and slightly evolved MS, typical of an early intermediate-age open cluster. The cluster MS consists of A and F-type stars and extends over a range of about 11 to 15 V-magnitude. The CM diagrams also show field star contamination beyond the MS and at the red giant colour range.

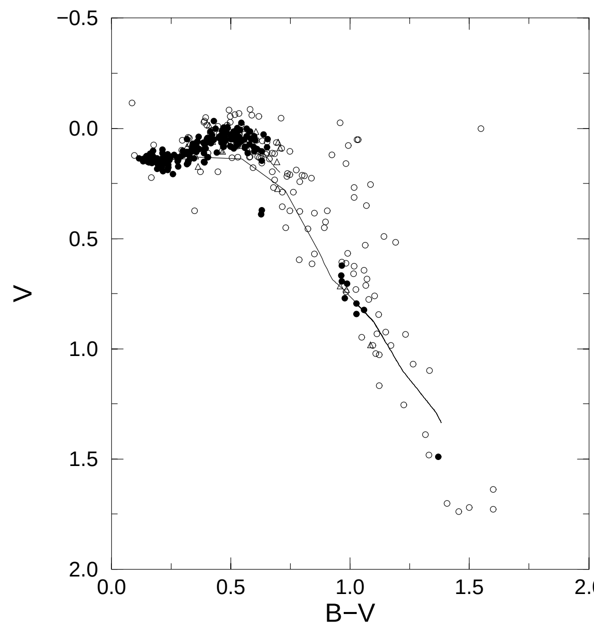

Fig. 6. The observed $(U-B,\, B-V)$ diagram for NGC 2539. Symbols are as in Fig. 4. The solid line represents the Schaller et al. (1992) isochrone for solar metallicity and log t = 8.80.

3.2. Red stars in the cluster field

In Paper I, seven stars were found to be cluster giants by means of photometric criteria. Later, Mermilliod & Mayor (1989) using

Coravel radial velocities confirmed the membership of these stars and added four new giants as cluster members. The eleven giants have also been represented by filled circles in the CM and CC diagrams. Stars 114, 209, 251, 317, 346, 447, 463 and 502 are located at the blue end of the giant branch forming a "clump" in the region identified by Cannon (1970) as the Population I analog of the horizontal branch in globular clusters. Star 663 is the brightest and reddest giant star in the diagrams, while stars 223 and 233 are yellow giants. Mermilliod & Mayor (1989) identified several spectroscopic binaries (SBs) among the cluster giants and obtained the orbital elements of three of them. In particular, the yellow giant 223 is a single-lined SB whose components are a clump red giant and a main sequence star. The remaining yellow giant 233 is also a suspected SB. Most probably both yellow giants are located in the Hertzsprung gap due to their binary nature. Two clump stars (114 and 209) are also SBs with faint companions.

It is interesting to note that three stars that had not been mentioned so far as possible red giants, lie on the clump zone in both CM diagrams. They are stars 229, 246 and 652, which should be considered as possible giant members of NGC 2539. Star 357 lies very close to the cluster yellow giants and might be a cluster member, while star 624 could also be a yellow giant, but it is a field star according to its radial velocity (Mermilliod & Mayor 1989).

3.3. Reddening, distance and age of NGC 2539

Assuming that we have correctly identified the cluster members, we have now determined reddening, distance modulus and age by fitting theoretical isochrones computed by Bertelli et al. (1994) for solar abundance (Y = 0.28, Z = 0.02). These isochrones include mass loss along the evolution of the stars and moderate overshooting. The resulting values are: $E(B-V)$ = 0.10, $E(U-B)$ = 0.07, $V - M_v$ = 11.00 and $\log t$(age) = 8.70. Unfortunately, however, the Padova isochrone corresponding to $\log t$ = 8.70 (represented by dashed lines in Figs. 4 and 5), does not fit the cluster giant branch stars as well as desired. The clump stars, for instance, are located up and blueward of the computed red giant loop in the CM diagrams. Note, however, that the observed stars follow the same pattern as the theoretical loop. Binarity certainly explains the location of one or perhaps both yellow giants in the Hertzsprung gap, but cannot explain the displacement of the eight clump stars. Some other Hyades-age open clusters, like NGC 1817 and NGC 2266, show a similar shift of the giant branch in the CM diagram. Harris & Harris (1977) and Kaluzny & Mazur (1991) have interpreted this anomaly as a consequence of the low metallicity of the clusters. It is well known that red giants become bluer when their metal abundances are lower (see, e.g., Hallgren & Cox 1970 or Harris & Deupree 1976). However, since the metallicity of the cluster giants in NGC 2539 computed by Clariá et al. (1989) from DDO and Washington photometry is nearly solar ([Fe/H] = 0.03 $\pm$ 0.09), this possible explanation should be ruled out. In fact, this is also true for NGC 1817 whose metal content recently derived by Clariá et al. (2000) is much higher ([Fe/H] = -0.12 $\pm$ 0.02) than the necessary one to explain the anomaly. However, the uncertainty on the exact value of the $\alpha = l/H_p$ mixing-length parameter is probably the cause of the mismatch of the isochrones in the red giant regions, as already observed in several open clusters. Although calibrated to reproduce the solar radius at the Sun age, it is not obvious that its value is a constant valid for all masses or evolutionary stages. The present observations would lead to the conclusion that it is not a parameter that can be fixed once for ever.

Nordström et al. (1997) have shown that the colours of Bertelli et al. (1994) are redder than any other isochrone set. For this reason, we redetermined reddening, distance and age of NGC 2539 from MS fitting using the stellar models computed by the Geneva group (Schaller et al. 1992). Assuming that the cluster has nearly solar metal content, the best fit for the MS is now achieved with $E(B-V)$ = 0.06, $V - M_v$ = 10.60 and $\log t$ = 8.80. As shown in Figs. 4 and 5, these new parameters give a good fit in the two CM diagrams and the isochrone for $\log t$ = 8.80 - represented by solid lines in Figs. 4 and 5 - reproduces well the morphology of the upper MS band in the $(V, B-V)$ diagram, including the binary ridge. This isochrone also better fits the red giant clump, although it is a little too bright and too red, as it is the case in several open clusters (see, e.g., Twarog et al. 1993, Daniel et al. 1994, Clariá et al. 1994).

Although Bertelli's isochrones do fit the observed data, the resulting cluster parameters are slightly different from those we obtain from the Geneva models, which have been finally adopted (Table 3). We have then adopted a visual absorption $A_{\rm V}$ = 3.0 $E(B-V)$ = 0.18. From the fitting procedure we estimated the mean errors to be about 0.02 mag for the reddenings and 0.06 mag for the visual absorption. Since in this case there is not a more direct way to determine the cluster foreground extinction, it is difficult to assert whether there is any differential reddening across the cluster. The resulting distance is d = 1210 pc, which implies z = 233 pc above the Galactic plane. Our distance is somewhat larger than that obtained in Paper I (910 pc), but it is intermediate between the values found by Becker & Fenkart (1971) or Joshi & Sagar (1986) and that of Pesch (1961). If we assume that the fitting errors are around 0.15 mag, our distance determination may be uncertain by about 12%. The cluster age turns out to be 630 Myr, practically the same as in Paper I, which places NGC 2539 within the Hyades-age group. The adopted isochrone properly adjusted to the derived reddening and distance values is plotted as a solid line in Figs. 4, 5 and 6.

In Paper I we noted that the mean masses of the red giants were too low compared to those of the turn-off. Now we can compare the giant masses with those computed by Schaller et al. (1992) for the post-helium flash (or clump) stars. According to these authors, at the adopted age of the cluster ($\log t$ = 8.80), stars located on the clump region have masses of about 2.5 $M_\odot$. In Paper I, using DDO photometric calibrations, the average mass of seven red giants turned out to be 1.3 $\pm$ 0.2 $M_\odot$, i.e., approximately half of their theoretical value. Unfortunately, this result could not be confirmed by any of the three SBs detected by Mermilliod & Mayor (1989), since all of them are single-lined SBs whose mass determination is very uncertain. Mass loss is a

Table 3. Summary of the results obtained for NGC 2539

Position		
α = 8^h 08.^{m}4 δ = -12^o 41$'$ (1950.0)		
l = 233^o 44' b = 11^o 07$'$ (1950.0)		
Distance		
V - M$_v$	: apparent distance modulus	= 10.60
E(B-V)	: selective absorption	= 0.06
A$_v$	: visual absorption (variable)	= 0.18
V$_o$ - M$_v$	: true distance modulus	= 10.42
d	: distance from the Sun	= 1210 pc
z	: distance from Galactic plane	= 233 pc
Age		
log t	: log age	8.80
t	: age	630 Myr
Dimension		
D	: angular diameter	= 21'
δ	: linear diameter	= 7.4 pc
Membership		
N(m)	: number of probable members	$\geq$ 169
N(RG)	: number of red giant members	= 11
N(V)	: number of variables	= 11
Structure of main sequence		
$(B-V)_o$	: blue turnoff	= -0.01
	: red turnoff	= +0.13
$(U-B)_o$	: blue turnoff	= -0.01
	: red turnoff	= +0.12
M_v	: clump mean magnitude	= -0.12
$(B-V)_o$	: clump mean colour	= +1.00
Integrated parameters		
M_v	: visual absolute mag.	= -3.83
$(B-V)_o$	: intrinsic $(B-V)$ colour	= +0.34
$(U-B)_o$	: intrinsic $(U-B)$ colour	= +0.11
$M/M_\odot$	: total mass	$>$ 400
π	: stellar density	= 0.72 stars pc^{-3}
ρ	: mean space density	= 1.03 $M_\odot$ pc^{-3}

very important mechanism in many phases of stellar stages and it has been the subject of several studies from observational and theoretical points of view (Antov & Popova 1989, D'Cruz et al. 1995). Despite this, it remains one of the most poorly understood aspects of the evolution of the stars. Anyway, Tripicco et al. (1993) and Yong et al. (1997), among others, have demonstrated that mass loss tends to evolve the stars blueward in the HR diagram in comparison to their normal course of evolution. We do not have at present any set of homogenoeus isochrones computed with different amounts of mass loss, so it is difficult to carry out a quantitative comparison of theory and observations. But the fact is that mass loss appears to be a likely option to explain, at least partially, the location of the red giants in NGC 2539.

Any way, the morphology of the red-giant clump in NGC 2539 is well reproduced by the evolutionary models, contrary to what happens in older clusters, and especially in NGC 1817 (Mermilliod et al. 2000). The latter cluster shows an elongated clump which spans almost two magnitudes. Therefore the changes, in the form of a mass spread, must appear later at smaller masses.

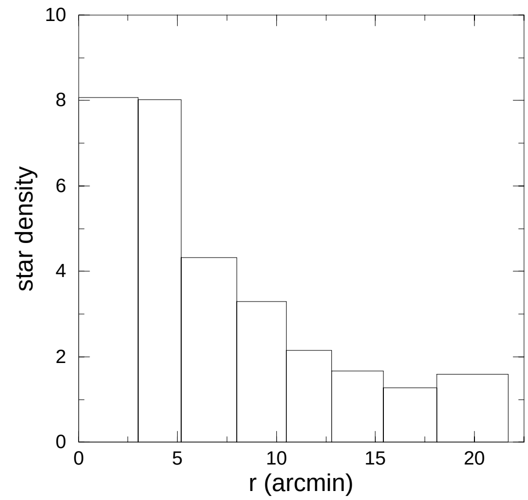

Fig. 7. Star counts in and around NGC 2539

3.4. Blue stragglers

Another interesting feature of the CM diagrams is the presence of three possible blue stragglers (BSs) nearly two magnitudes above the turn-off region. They lie well to the right of the ZAMS in both CM diagrams and two of them, 610 and 653, are located in the outer region of the cluster. The remaining BS candidate 623 is the only one considered to be a potential cluster member in Ahumada & Lapasset's (1995) BS catalogue. This star is located closer to the center but its radial velocity is not in agreement with that of the cluster red giants (González 2000). Most probably these three stars are foreground field objects.

3.5. Cluster diameter

To estimate the diameter of NGC 2539, star counts in the rings shown in Fig. 1 were performed to the limiting magnitude of the plate. We plotted in Fig. 7 the number of stars per unit area as a function of the mean distance of each ring from the cluster center. With the purpose of extending our counts around the cluster, we added three rings to those in Fig. 1. The following conclusions may be drawn from the star counts: (1) Stars are clearly concentrated in the four inner regions, while the star density in rings V and VI is almost similar to the field star density measured far away from the cluster. (2) Out of 169 stars considered to be probable MS cluster members in Sect. 3, 144 ($\sim$ 85%) are inside rings I to IV. Thus we adopt the radius of ring IV (10.5 arcmin) as the cluster angular radius. (3) The estimated radius leads to a linear diameter of 7.4 pc, so that the minimum stellar density amounts to 0.72 stars pc^{-3} if the red giants are included. This diameter is about 30% smaller than that calculated by Pismis & Bozkurt (1977) from star counts on Schmidt plates.

4. Summary and conclusions

The present photometric study of NGC 2539 has yielded the following main results: (1) The CM and CC UBV diagrams reveal a well-defined main sequence consisting of A and F-type stars. (2) From these diagrams, 169 stars brighter than V = 15.0 were found to be probable cluster members with a mean reddening $E(B-V)$ = 0.06 and a true distance modulus $V_0 - M_v$ = 10.42 (r = 1210 pc). (3) Using the main sequence fitting method by theoretical isochrones, an age of 630 Myr has been derived, which places this cluster within the Hyades-age group. (4) NGC 2539 also possesses at least 11 evolved stars, 8 of them forming a typical red-giant clump. These clump stars are located blueward of the post He-flash star models in the HR diagram. Both, binarity and metallicity appear to be unlikely options to explain this anomaly. The uncertainty on the exact value of the mixing-length parameter is probably the cause of the mismatch of the isochrones in the red giant regions. However, mass loss during the evolution of these stars might also partially account for the location of the clump stars in the HR diagram. Further investigations on these options are clearly warranted.

NGC 2539 is an interesting Hyades-age open cluster. The contamination of its upper main sequence by field stars appears to be negligible. This, in combination with a well populated giant branch, makes NGC 2539 a very useful target for testing of theoretical isochrones. In addition, because of its age similarity with the Hyades, Praesepe and NGC 6633 open clusters, it contains certainly several Am stars. A direct spectroscopic search for such stars would be warranted to increase the number of observed clusters and the statistics of detected stars in clusters of different ages. The way the frequency of Am stars changes in function of the parent-cluster ages is still poorly documented.

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