Studies of binary star cluster candidates in the bar of the LMC. II. *

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Abstract. Binary clusters account for more than 10% of the cluster population in the Magellanic Clouds. Statistically fewer than 50% of the found pairs are expected to be chance superpositions. We estimated the cluster encounter rate and suggest that tidal capture is an unlikely formation scenario for the formation of binary clusters. Thus, most true binary clusters can be expected to have formed together.

Here we present a study of three binary cluster candidates which are located in the bar of the LMC. NGC 1971 & NGC 1972 are situated in the association LH 59 in the eastern part of the bar. A third star cluster, NGC 1969, is close enough to this pair that all three objects may constitute a triple system. We present the first age determination that is based on CMDs for these star clusters. Our findings suggest that all three clusters are young (40-70 Myr) and may have been formed in the same GMC. It cannot clearly decided whether the clusters are physically interacting or not.

NGC 1894 & SL 341 are located at the south-western rim of the LMC bar. This pair is studied in detail for the first time: The isopleths of both clusters reveal an elliptical shape. Whether this might be interpreted as a sign of interaction or is a peculiarity which is shared with a large amount of LMC star clusters which show higher ellipticities than their counterparts in the Milky Way remains unclear. From our age determination we find that both clusters are coeval with an age of 55 ± 5 Myr. This makes a formation from the same GMC a likely scenario.

SL 385 & SL 387 are a close pair in the western part of the LMC bar. We derived ages of 170 ± 30 Myr for SL 385 and ≥ 250 for SL 387. The large age difference makes it unlikely that these two clusters formed in the same GMC.

Key words: Magellanic Clouds – Hertzsprung-Russel (HR) and C-M diagrams – Galaxies: star clusters: NGC 1971, NGC 1972, NGC 1969 – Galaxies: star clusters: SL 385 & SL 387 – Galaxies: star clusters: NGC 1894 & SL 341

1. Introduction

The Magellanic Clouds offer the unique possibility to study star clusters in general and binary clusters in particular. These two companion galaxies are close enough to resolve single stars, but distant enough to make the detection of close pairs of star clusters an easy task. Bhatia & Hatzidimitriou (1988), Hatzidimitriou & Bhatia (1990), and Bhatia et al. (1991) have surveyed the Magellanic Clouds in order to catalogue the binary cluster candidates. The maximum projected centre-to-centre separation of the components of a pair chosen for inclusion in the list of candidates was 18 pc, which corresponds to ≈ 1.3′ in the Large Magellanic Cloud (LMC). A binary cluster with larger separation may become detached by the external tidal forces while shorter separations may lead to mergers (Sugimoto & Makino 1989; Bhatia 1990). Two clusters may appear to be a binary cluster due to chance line-up while in fact being at different distances within the Magellanic Clouds and not gravitationally bound to each other. An estimation of the number of such chance-pairs of objects (Page 1975) revealed that less than half of all pairs found are expected statistically. As considerably more double clusters were found, this strongly suggests that at least a subset of them must be true binary clusters, i.e., clusters that are formed together and/or may interact or even be gravitationally bound.

Star clusters form in giant molecular clouds (GMCs), but the details of cluster formation are not yet totally understood (Elmegreen et al. 1999). Fujimoto & Kumai (1997) suggest that star clusters form through strong collisions between massive gas clouds in high-velocity random motion. Oblique cloud-cloud collisions result in compressed sub-clouds which revolve around each other and form binary or multiple clusters. Binary star clusters are expected to form more easily in galaxies like the Magellanic Clouds, whereas in the Milky Way the required large-scale high-velocity random motions are lacking. Indeed only few binary clusters are known in our own Galaxy.

The probability of tidal capture of one cluster by another one is small (Bhatia et al. 1991), but becomes more probable in dwarf galaxies like the Magellanic Clouds with small velocity dispersion of the cluster systems (van den Bergh 1996). In that case the clusters would be gravitationally bound, but age differences are likely. Tidal interactions between clusters can be
traced using isodensity maps (de Oliveira et al. 1998; Leon et al. 1999). However, Vallenari et al. (1998) estimated a cluster encounter rate of $\frac{dN/dt}{dt} \sim 1 \cdot (10^{7} \text{yr})^{-1}$. This makes tidal capture of young clusters very unlikely. Interaction between LMC and SMC might have led to a higher cluster formation rate and, due to the dynamical perturbation, a higher encounter rate might be possible (see Vallenari et al. 1998 and references therein).

The formation of low-mass star clusters tends to proceed hierarchically in large molecular complexes over several $10^{7}$ years (e.g., Efremov & Elmegreen 1998). Leon et al. (1999) suggest that in these groups the cluster encounter rate is higher and thus tidal capture is more likely: Binary clusters are not born together as a pair with similar ages but are formed later through gravitational capture. An observational test of this scenario would require the detection of evidence of tidal interactions between clusters, whose age differences need to be compatible with the survival times of GMCs.

Another binary cluster formation scenario is introduced by Theis et al. (1997) and Ehlerová et al. (1997): Exploding supernovae close to the centre of a giant molecular cloud sweep up the outer cloud material within a few Myrs and accumulate it in the shell. The large amount of matter makes the shell prone to gravitational fragmentation and finally to the formation of many open cluster-like associations. In case of a dense ambient medium outside the cloud or a very massive original molecular cloud the shell can be strongly decelerated resulting in a recollapse. A galactic tidal field acting on this recollapsing shell can split it into two or more large clusters, thus forming coeval twin clusters which are, however, not gravitationally bound (Theis et al. 1998). The fragments may stay together for a long time, though they are gravitationally unbound. The evolution of their spatial separation mainly depends on the shape of the shock front at the time of fragmentation.

Depending on their masses and separations binary clusters will eventually merge or become detached. A merged binary cluster will have one single but elliptical core (Bhatia & McGillivray 1988) which can also be found in the young blue populous clusters of the Magellanic Clouds. Can mergers of former binary star clusters be responsible for at least some of the blue populous clusters in the LMC?

We are studying binary cluster candidates in the Magellanic Clouds to investigate whether the cluster pairs are of common origin and if they show evidence for interaction. While it is not possible to measure true, deprojected distances between apparent binary clusters an analysis of their properties can give clues to a possible common origin.

In this paper, we investigate three binary cluster candidates, namely NGC 1894 (also known as SL 344, Shapley & Lindsay 1993), or BRHT 8a, see Bhatia et al. (1998) & SL 341 (or BRHT 8b), NGC 1971 & NGC 1972 (or SL 481 (BRHT 12a) & SL 480 (BRHT 12b), and SL 387 & SL 389 (or BRHT 35a & BRHT 35b). All three cluster pairs are located in the bar of the LMC.

NGC 1894 and SL 341 constitute a close pair at the southwestern rim of the LMC bar. Only the bigger cluster NGC 1894 appears in the list of Bica et al. (1996) as an SWB type II cluster (Searl et al. 1980). Here we present the first detailed study of this candidate binary cluster.

NGC 1971 and NGC 1972 are situated in the association (or stellar cloud, Lucke & Hodge 1970) LH 59 in the eastern part of the LMC bar, close to the geometrical centre of this galaxy (see Hodge & Wright 1970). A third cluster, NGC 1969 (or SL 479), is located within 1.5 ($\approx$ 22 pc). Bica et al. (1996) classified the cluster pair to be of SWB type II while the third cluster belongs to the next older class SWB type III. So far, no accurate ages based on colour magnitude diagrams (CMDs) have been obtained for this potential triple cluster system.

The third cluster pair, SL 385 and SL 387, is also located close to the geometrical centre, but in the western part of the LMC bar. According to ages for a large sample of star clusters, derived on the base of integrated colours, Bica et al. (1996) propose an age gradient of the LMC bar. Younger clusters are predominantly found in the eastern part, while older clusters of SWB type III and higher are concentrated to its western end. From integrated colours Bica et al. (1996) find these two clusters to be coeval, while Vallenari et al. (1998) determine a large CMD-based age difference of $\sim$ 350 Myr between the clusters. Based on subgiant density profiles Leon et al. (1999) suggest that the two clusters may constitute a true binary cluster with physical interaction.

This paper is organized as follows. In Sect. 2 we describe the photometric data in general. Stellar density maps are presented in Sect. 3. The following section describes the CMDs for the components of each cluster pair. Ages for each cluster are derived and compared with previous studies. In Sect. 4 we estimate the probability of cluster encounters in the LMC’s bar and disk. In Sect. 5 we give a summary and discuss the results.

2. Photometric observations and data reduction

The cluster pair NGC 1894 & SL 341 was observed on February 8, 1995, with ESO Multi-Mode Instrument (EMMI) using the red arm (Red Imaging and Low dispersion spectroscopy – RILD) at the ESO New Technology Telescope (NTT) at La Silla. The ESO #36 chip (TEK 2048 $\times$ 2048) was used with a pixel scale of $0.27^\prime\prime$. The resulting field of view is $9.2^\prime \times 8.6^\prime$. The data were obtained with the Bessell $B$, $V$, $R$ and Gunn $i$-filters.

The data for the other two binary cluster candidates were obtained on March 23 (NGC 1971 & NGC 1972), and 27 (SL 385 & SL 389), 1994, with the ESO Faint Object Spectrograph and Camera 2 (EFOSC 2) at the ESO/MPG 2.2 m telescope at La Silla. A 1024 $\times$ 1024 coated Thomson 31156 chip (ESO #19) was used with a pixel scale of $0.34^\prime$ resulting in a field of view of $5.8^\prime \times 5.8^\prime$. These data were obtained with the Washington $T1$, Gunn $q$ (which resembles Washington $M$), and Gunn $i$ (which corresponds to Washington $T2$) filters used at the 2.2 m telescope. In order to avoid flatfielding problems near the edges of the exposures taken in Washington-filters, each image was cut out resulting in a field of view of $4.3^\prime \times 3.5^\prime$. The problem is worst in $T1$ and least in Gunn $i$. Images of the binary cluster candidates are shown in Figs. 1, 3, and 5.
Table 1. Observing log

| Object          | Filter | Exp.time [sec] | Seeing ["] |
|-----------------|--------|----------------|------------|
| NGC 1971/NGC 1972 | Gunn g  | 600            | 1.2        |
| NGC 1971/NGC 1972 | Gunn g  | 60             | 1.4        |
| NGC 1971/NGC 1972 | T1      | 300            | 1.3        |
| NGC 1971/NGC 1972 | T1      | 30             | 1.3        |
| NGC 1971/NGC 1972 | Gunn i  | 300            | 1.1        |
| NGC 1971/NGC 1972 | Gunn i  | 30             | 1.1        |
| SL 385/SL 389   | Gunn g  | 600            | 1.3        |
| SL 385/SL 389   | Gunn g  | 60             | 1.5        |
| SL 385/SL 389   | T1      | 240            | 1.2        |
| SL 385/SL 389   | T1      | 30             | 1.1        |
| SL 385/SL 389   | Gunn i  | 240            | 1.4        |
| SL 385/SL 389   | Gunn i  | 30             | 1.5        |
| SL 385/SL 389   | Gunn i  | 30             | 1.2        |
| NGC 1894/SL 341 | B       | 300            | 1.2        |
| NGC 1894/SL 341 | B       | 40             | 1.3        |
| NGC 1894/SL 341 | V       | 130            | 1.3        |
| NGC 1894/SL 341 | V       | 10             | 1.3        |
| NGC 1894/SL 341 | R       | 180            | 1.0        |
| NGC 1894/SL 341 | R       | 10             | 0.9        |
| NGC 1894/SL 341 | Gunn i  | 180            | 1.0        |
| NGC 1894/SL 341 | Gunn i  | 10             | 0.9        |

Table 1 gives an observing log.

After standard image reduction with MIDAS, profile fitting photometry was carried out with DAOPHOT II (Stetson [1991]) running under MIDAS.

The photometry was transformed using standard fields observed in the same nights the object data were obtained. For the Washington data the standard fields SA 110 and SA 98 (Geisler [1990]), and for the Bessell data the standard fields around Rubin 149, PG 1942, PG 0942 and the SA 98 (Landolt [1992]) were used.

We applied the following transformation relations:

\[ g - G = z_G + a_G \cdot (G - T1) \]
\[ t1 - T1 = z_{T1} + a_{T1} \cdot (G - T1) \]
\[ i - I = z_I + a_I \cdot (G - T1) \]
\[ b - B = z_B + a_B \cdot (G - V) \]
\[ v - V = z_V + a_V \cdot (G - V) \]
\[ r - R = z_R + a_R \cdot (G - V) \]
\[ i - I = z_I + a_I \cdot (G - V) \]

where \( X \) is the mean airmass during observation, capital letters represent standard magnitudes and colours, and lower-case letters denote instrumental magnitudes after normalizing to an exposure time of 1 sec. The resulting colour terms \( c_i \), zero points \( z_i \), and atmospheric extinction coefficients \( a_i \) are listed in Table 2 for all nights.

3. Stellar density maps

We investigate the stellar density distribution in and around the clusters by counting the number of stars in square cells of 20 pixels (corresponding to 6.8 or 1.7 pc) length. For the images taken with the ESO/NTT we choose square cells of 26 pixels length. In order to enhance the features of the star clusters only stars with magnitudes and colours as can be found in the clusters are included. In this way, a falsification by field stars outside the selected magnitudes and colours is avoided. To make density structures and possible signs of interaction better visible we applied a \( 3 \times 3 \) average filter for image smoothing. The procedure is described in more detail in Dieball & Grebel (1998). The stellar density maps are shown in Figs. 2, 4 and 8.

3.1. NGC 1971 & NGC 1972:

Three clusters are covered by the CCD images (see Fig. 1) which may constitute a triple system: the cluster pair NGC 1971 & NGC 1972 (Bhatia et al. 1991) and to the northwest a third, close cluster is located: NGC 1969. These clusters are situated in the eastern part of the bar of the LMC. Assuming a distance modulus of 18.5 mag (Westerlund [1997]) the projected distances between the clusters are 54.6 or 13.3 pc (NGC 1971 – NGC 1972), 76.7 or 18.6 pc (NGC 1971 – NGC 1969) and 84.6 or 20.6 pc (NGC 1972 – NGC 1969).

For the density plots only stars with \( T2 \leq 15.5 \) (upper main sequence and supergiants) or \( T2 \leq 19.5 \) mag and \( M - T2 \leq 0.6 \) mag (lower main sequence without red clump stars) are considered. NGC 1969 is a loose extended cluster. It stands out much more clearly on the stellar density map in Figure 2 than in Fig. 1. NGC 1971 is the most prominent and populous of the three clusters and seems to be somewhat elongated towards the other two clusters. However, a connection between the clusters as can be seen e.g. for SL 538 & NGC 2006 (Dieball & Grebel 1998) is not visible from the stellar density map.

3.2. SL 385 & SL 387:

An image of SL 385 & SL 387 is shown in Fig. 8. This double cluster is located in the inner western part of the LMC bar. The
Fig. 1. T1-image of the cluster pair NGC 1971 & NGC 1972. North is up and east to the left. The field of view is $4'3 \times 3'5$. This candidate binary cluster is located in the bar of the LMC close to the geometrical centre. To the northwest a third close cluster is located: NGC 1969.

Fig. 2. Stellar density in and around the three clusters NGC 1971, NGC 1972 and NGC 1969. One pixel of the density map corresponds to $20 \times 20$ pixels in the CCD exposure. NGC 1969 is an extended low-density cluster. NGC 1971 is also quite elongated.

Project distance between the clusters is $45''6$ corresponding to 11.1 pc.

The selection criterion for the isopleth was $M - T2 \leq 1.8$ and $T2 \leq 19$ mag. The stellar density (see Fig. 2) between the clusters seems to be enhanced. The enhancement is between 2 and $3\sigma$ above the background surrounding the binary cluster candidate. To the southwest another separate enhancement is visible, maybe marking the location of a third, fainter cluster. However, this enhancement is slightly lower than between the cluster pair, but still between 2 and $3\sigma$ above the background.

Fig. 3. Same as Fig. 1 but for the cluster pair SL 385 & SL 387. This candidate binary cluster is located in the inner western part of the LMC bar.

Fig. 4. Star density map of the cluster pair SL 385 & SL 387. The stellar density between the two clusters is enhanced. Note the separate enhancement to the southwest of the double cluster.

Leon et al. (1999), whose data for SL 385 & SL 387 go to fainter magnitudes than ours (see Sect. 3), were able to distinguish between contributions from the two clusters to the possible tidal features around them by considering the density distribution of stars near the main-sequence turnoff and along the subgiant branch of both clusters. Their data show that the cluster-like density enhancement south of SL 385 may be part of an arced tidal tail originating from SL 387. The density extension at the northern edge of SL 385 in contrast appears to be part of a tidal feature belonging to this cluster. These data appear to be the strongest indication of tidal interactions between two clusters found so far. For a discussion of the ages see Sect. 4.
3.3. NGC 1894 & SL 341:

An image of the cluster pair NGC 1894 & SL 341 is presented in Fig. 5. The two clusters are situated at the south-western rim of the LMC bar. The projected distance between the clusters is 79.5′ corresponding to 19.3 pc. Thus, this pair shows the largest separation of our sample.

Only stars with $16 \leq V \leq 19$ mag and $B - V \leq 0.5$ mag are included in the density map (Fig. 6). NGC 1894 is more pronounced and has an elliptical shape. No significant enhancement between the clusters can be seen. The star density increases towards the LMC bar in the north-east and is much lower towards the opposite direction.

4. Colour Magnitude Diagrams and Isochrone fitting

We derived ages for all star clusters by comparing CMDs with isochrones. The isochrones used are based on the stellar models of the Geneva group (Schaerer et al. 1993). The transformation to the Washington system was performed by Roberts & Grebel (1994).

To derive the CMDs for each of the clusters we cut out a circular area placed around the optical centre of each cluster. Cluster radii were determined from first stellar density maps which included all stars. An investigation of the star density plots suggests that all or at least most cluster stars are located inside the chosen areas. The cluster CMDs were compared with the CMDs of the surrounding field and a statistical field star subtraction was applied to clear the cluster CMDs from contaminating field stars which might affect the age determination.

The CMDs of all clusters and the surrounding fields are plotted in Figs. 7, 8, 9, and 10. Overplotted on the CMDs are the best fitting isochrones.

We only present the $T2$ versus $M - T2$ and $V$ versus $B - V$ CMDs. CMDs with other colours lead to the same results.

For all isochrone fits we adopt a distance modulus of 18.5 mag (Westerlund 1997) and a metallicity of $Z = 0.008$ corresponding to $[Fe/H] \approx -0.3$ dex which was found by various authors for the young field star population of the LMC (Russell & Bessell 1989, Luck & Lambert 1992, Russell & Dopita 1992, Thévenin & Jasiewicz 1992). We derive reddenings for our selected cluster areas and compare our values with the reddening maps of Burstein & Heiles (1982) and Schwering & Israel (1991).

Galactic field stars might contaminate our observed area. In order to judge whether foreground stars might affect our age determination or not we compare our CMDs with the number of galactic field stars towards the LMC estimated by Ratnatunga & Bahcall (1985). In Table 3 we present their counts scaled to our field of view of 4′3 × 3′5 and 9′2 × 8′6, respectively.

The CMDs and the isochrone-fitting are described in more detail in the following subsections.
Fig. 7. CMD of the triple cluster NGC 1971, NGC 1972, and NGC 1969. Large dots represent stars that remain after field star subtraction and thus (statistically) belong to the cluster. Small dots represent field stars contaminating the cluster area (radius $30''$ for NGC 1971 and NGC 1969, $27''$ for NGC 1972). The best fitting isochrones are overplotted with thick lines. Isochrones of the same age, but with a different reddening, are overplotted as thin lines, their properties are given in brackets. An isochrone resulting in an age of 63 Myr gives a good fit to the main sequence and the supergiants for NGC 1971. Age determination for NGC 1969 is more difficult since both the 50 Myr and the 80 Myr isochrones give good fits to either the brightest main sequence stars or the red supergiants. NGC 1972 may be younger with 50 Myr (dotted lines) or even 32 Myr (solid lines). Mean error bars are given at the right side in the CMD of NGC 1971. For a more detailed discussion of the isochrone fits see text Table 3.

Table 3. Number of foreground stars towards the LMC calculated from the data of Ratnatunga & Bahcall (1985), scaled to our fields of view of $4.3' \times 3.5'$ and $9.2' \times 8.6'$

| colour range | 13-15 | 15-17 | 17-19 | 19-21 | 21-23 |
|--------------|-------|-------|-------|-------|-------|
| $B - V < 0.8$ | 0.6   | 1.3   | 1.4   | 2.9   | 2.7   |
| $0.8 < B - V < 1.3$ | 0.2   | 1.2   | 2.4   | 1.9   | 3.3   |
| $1.3 < B - V$ | 0.0   | 0.3   | 1.7   | 5.7   | 13.1  |

| B - V | 13-15 | 15-17 | 17-19 | 19-21 | 21-23 |
|-------|-------|-------|-------|-------|-------|
| $B - V < 0.8$ | 3.2   | 6.8   | 7.4   | 15.2  | 14.2  |
| $0.8 < B - V < 1.3$ | 1.1   | 6.3   | 12.6  | 10.0  | 17.3  |
| $1.3 < B - V$ | 0.0   | 1.6   | 8.9   | 30.0  | 68.9  |

4.1. NGC 1971 & NGC 1972 & NGC 1969:

The clusters’ CMDs are shown in Fig. [1]. These CMDs represent all stars located in a circular area with a radius of 90 pixels corresponding to $30'/6$ or 10.4 pc. NGC 1972 is the smallest of all three clusters so we chose a smaller radius of 80 pixels corresponding to $27''$ or 9.2 pc. The stellar density plot (Fig. [2]) suggests that all cluster stars are well within the chosen areas.

Each cluster CMD shows a wide blue main sequence and contains few supergiants. The width of the main sequence is caused in part by photometric errors (average seeing $1''$, see the representative error bars in the CMD of NGC 1971) and crowding. The latter one is a major problem in the densely populated LMC bar. Rotating stars, binaries, and Be stars also lead to a widening, but will broaden the main sequence only to the red side. Consequently, we do not fit the isochrones midway through the main sequence but bluewards from the middle. The small number of supergiants is expected for poor clusters. Also red clump stars and red giants are present in the CMDs. Small dots represent all stars which are located inside our selected areas, while large dots denote the stars which remain after field star subtraction and thus, statistically, belong to the star cluster. It is evident that red clump stars and red giants, which are mainly represented by small data points, do not belong to the star clusters, while most main sequence stars and supergiants are probable cluster members (represented by large dots).

After field star subtraction three red and two blue supergiants remain in the CMD of NGC 1971. They are located within $13''6$ radius except for the brightest red one which is located within $17''$ radius. The field has a few supergiants in the same magnitude range indicating a similar age (see Sect. [4.4]).
Scaled to the same area the ratio of cluster to field supergiants is 5 to 2. We are confident that most if not all of the 5 supergiants belong to the cluster since they are clearly concentrated to the cluster’s centre. An isochrone resulting in an age of 63 Myr and a reddening of $E_{M-T_2} = 0.03$ mag gives a very good fit to the 5 supergiants. Also the apparent turnoff of the main sequence is well represented. Our assumed reddening is somewhat low compared to the reddening maps of Burstein & Heiles (1982) or Schwering & Israel (1991). Both groups found redenings of $E_{B-V} \approx 0.09$ mag corresponding to $E_{M-T_2} \approx 0.14$ mag (see Grebel & Roberts 1995, their Table 5, for the transformation of extinctions in different filter systems). For comparison we plotted in thin lines also isochrones of the same age but with a reddening as suggested by Burstein & Heiles (1982). As can be seen, the main sequence, especially its upper bright part, is not as well represented as with the isochrones of lower reddening.

NGC 1972 is the smaller one of the cluster pair which is also visible from the sparser main sequence. Four red supergiants remain as likely cluster members after statistical field star subtraction. The best fitting isochrones result in slightly younger ages of 32 Myr (solid lines) or 50 Myr (dotted lines). Both isochrones give a good fit, thus we adopt an age of $40 \pm 10$ Myr for NGC 1972. The isochrones drawn with thick lines are based on a reddening of $E_{M-T_2} = 0.14$ mag as suggested by Burstein & Heiles (1982), and give a good fit to the main sequence, both the lower and the brighter part. Isochrones based on a reddening of $E_{M-T_2} = 0.03$ mag (as assumed for NGC 1971) are plotted with thin lines and fit the blue side of the main sequence, which might underestimate the photometric error. In the case of NGC 1972 a higher reddening seems to give better fits.

The CMD of NGC 1969 shows more supergiants remaining after field star subtraction than the CMDs of the other two clusters. They indicate the young age of this cluster, but due to their location in a magnitude range between 13 and 15 mag in $T_2$ they make an age determination more difficult. Two isochrones with ages of 50 Myr (solid line) and 80 Myr (dotted line) are overplotted on the CMD. The 50 Myr isochrone gives the best fit to the apparent main sequence turnoff. However, the 80 Myr isochrone fits best to the red supergiants. We adopt an age of $65 \pm 15$ Myr for this cluster. The lower reddening of $E_{M-T_2} = 0.03$ mag (see thick lines) gives a better fit than the value suggested by Burstein & Heiles (1982) (isochrones drawn with thin lines).

In all cluster CMDs a population of stars between 16.5 mag and 17 mag in $T_2$ can be seen. These data points can be fitted with 200 or 250 Myr isochrones. However, the distribution of these stars in our field of view is not concentrated towards the location of the three star clusters, as is, in contrast, the distribution of the bright main sequence stars (brighter than 17 mag) and bright supergiants. This is an indication of the young age of the star clusters. Thus we do not plot these isochrones in the CMDs. The few red stars at $T_2 \approx 16.75$ mag remain in the clusters CMDs due to the imperfect statistics of the statistical field star subtraction.

For NGC 1971 and NGC 1969 we derived a reddening of $E_{M-T_2} = 0.03$ mag corresponding to $E_{B-V} = 0.02$ mag which is somewhat low compared to the reddening maps of Burstein & Heiles (1982) or Schwering & Israel (1991). Both groups suggest a reddening of $E_{B-V} \approx 0.09$ mag ($E_{M-T_2} \approx 0.14$ mag). Considering the photometric and the calibration errors and the uncertainty of the isochrone fits caused by the width of the main sequence, the error of our reddening values might be of the order of 0.06 mag, which makes our values consistent with the findings of Burstein & Heiles (1982) or Schwering & Israel (1991). However, our clusters cover small areas with a maximum radius of 30". Such small scale variations cannot be resolved with either of the two reddening maps which are derived on scales of 36" (Burstein & Heiles 1982) or 48" (Schwering & Israel 1991), respectively. For a $1.9^\circ \times 1.5^\circ$ area of the LMC Harris et al. (1977) provided reddening maps which show variations on smaller scales. Zaritsky (1999) investigated a larger region, including the field studied by Harris et al. (1977), and found a dependence between extinction and stellar populations. Their fields do not include the LMC bar, so none of our clusters is included in the region investigated by them. Another explanation for our low reddening values could be that the star clusters might be located in front of the LMC bar.

4.1.1. Comparison to surface photometry:

Our study leads to the first ages for NGC 1969, NGC 1971, and NGC 1972 derived from a comparison between theoretical isochrones and CMDs.

Bica et al. (1992, 1996) derived ages for a large sample of LMC clusters using $UBV$ integrated photometry. Their investigation includes our binary cluster candidates. However, age determinations based on integrated colours are less precise than ages derived from CMDs. Geisler et al. (1997) point out that a few bright stars can influence the age determination based on integrated photometry, making the result dependent on the chosen aperture. A comparison between the ages derived by Bica et al. (1996) and our results can be found in Table 4.

According to Bica et al. (1996) both NGC 1971 and NGC 1972 have SWB type II, corresponding to an age of 30 to 70 Myr. NGC 1969 belongs to SWB type III which denotes an age between 70 to 200 Myr. Their results are mainly consistent with our work, but as can be seen from Table 4 the age differences between the components of the cluster pairs cannot be resolved from integrated photometry. NGC 1969 is the oldest component of the triple cluster, which was also found by Bica et al. (1996). However, within the errors all three clusters can be considered as nearly coeval. Indeed, the integrated colours of NGC 1969 from Bica et al. (1996) place this cluster in a two colour diagram in the SWB III but near the SWB II region. Based on our results this cluster could as well be of SWB type II.
Fig. 8. CMD of the cluster pair SL 385 and SL 387. Overplotted on the CMDs are the best fitting isochrones. Small and large dots denote all stars which can be found in the chosen area of 27’’ radius, only the larger data points remain after field star subtraction. Middle size dots in the CMD of SL 387 represent stars that are located in an inner area with 13’’ radius. Isochrones resulting in an age of 130 – 200 Myr give a good fit to the main sequence turnoff and the red supergiants in SL 385. SL 387 seems to be older, note the large amount of evolved stars. Fitting the brightest of these stars results in a lower age limit of ≥ 250 Myr. For a detailed discussion see text.

4.2. SL 385 & SL 387:

Fig. 8 shows the CMDs for this binary cluster candidate.

Following the stellar density distribution we consider stars within a radius of 80 pixels corresponding to 27’’ or 9.2 pc as likely members for SL 385 and SL 387. Both clusters appear to have similar sizes, see Figs. 3 and 4. Again, both large and small dots represent all stars located inside the chosen region while only the large data points remain after statistical field star subtraction.

The CMD of SL 385 shows a wide main sequence (average seeing 1’’4) and red giants in a magnitude range between $T_2 \approx 15.5$ to 16.5 mag and a colour range of $M - T_2 \approx 0.8$ to 1.5 mag. Most of the red clump stars vanish after field star subtraction (small dots), indicating the younger age of this star cluster. Overplotted on the CMD are the best fitting isochrones which represent the location of the cluster’s red giants as well as the apparent main sequence turnoff, resulting in an age of 130 Myr (solid line), 160 Myr (dotted line) and 200 Myr (dashed line). The isochrone resulting in the youngest age of 130 Myr gives the best fit to the main sequence turnoff, but will not fit all supergiants. The 160 Myr isochrone represents the supergiants well, and gives also a reasonably good fit to the main sequence. Also the 200 Myr isochrone would fit to the supergiants but seems to underestimate the luminosity of the main sequence turnoff. The luminosity difference between the apparent main sequence turnoff and the He-core burning giants results in a slight age difference (130 Myr or 200 Myr, respectively). Since we cannot reject either the younger or the older isochrone we adopt an age of 170 ± 30 Myr.

Such a discrepancy between the main sequence turnoff and red giants luminosities was noticed in the CMDs of various other LMC star clusters. Two prominent examples are NGC 1866 and NGC 1850 (see Brocato et al. 1989, Vallenari et al. 1994b, Lattanzio et al. 1991, Brocato et al. 1994). Unresolved binary stars which could increase the luminosity of the main sequence turnoff were proposed as one explanation. However, as Vallenari et al. (1994b) point out, no direct evidence for a significant population of binary stars could be found. A good representation of the observed CMDs through simulated ones was achieved by Lattanzio et al. (1991), who took both unresolved binaries and semiconvection into account.

Isochrone fitting to the CMD of SL 387 is much more difficult. The location of the main sequence turnoff cannot be determined with confidence, since our data are not deep enough. The main sequence is affected by crowding and shows a lot of scatter. The turnoff point is located at $T_2 \approx 18$ mag, at least one magnitude fainter than in SL 385 ($T_2 \approx 17$ mag). Dots of three different sizes are plotted in the CMD. The smallest dots denote the stars which are rejected by field star subtraction.
Most red clump stars seem to belong to the field population (smallest dots) but we see a lot of stars around $M - T2 = 0.5$ mag between main sequence and red clump which remain after field star subtraction (medium-sized and largest dots). These stars can also be seen in Vallenari et al. (1998), their Figs. 2 (left, CMD of SL 387) and 4 (left, CMD of SL 268). It seems likely that the determined colour of these stars is an effect of the severe crowding in the cluster’s centre. The isochrone which fits best to these stars has an age of 250 Myr (short dashed line). The large dots in the CMD denote the cluster stars in the outer region with a radius of 13"/6. As can be seen, the brightest of the stars in question are situated in the cluster centre. The isochrone which fits best to these stars has an age of 250 Myr (short dashed line). The large dots in the CMD denote the cluster stars in the outer region with a radius of 13"/6. As can be seen, the brightest of the stars in question are situated in the cluster centre. The isochrone which fits best to these stars has an age of 250 Myr (short dashed line).

Large dots represent the stars that are located in an inner region with the severe crowding in the cluster’s centre. The isochrone which fits best to these stars has an age of 250 Myr (short dashed line). The large dots in the CMD denote the cluster stars in the outer region with a radius of 13"/6. As can be seen, the brightest of the stars in question are situated in the cluster centre. The isochrone which fits best to these stars has an age of 250 Myr (short dashed line).

However, neither age is trustworthy. Our data allow us only to set a lower limit for the age of SL 387 of $\geq 250$ Myr.

For all isochrone fits we derived a reddening of $E_{M-T2} = 0.05 \pm 0.01$ mag corresponding to $E_{B-V} = 0.03$ mag which is again lower than the values derived by Burstein & Heiles (1982) or Schwering & Israel (1991) who found $E_{B-V} \approx 0.09$ mag (corresponding to $E_{M-T2} \approx 0.14$ mag) (see Sect. 4.1 for the discussion).

4.2.1. Comparison to previous age determinations:

$UBV$ surface photometry for SL 385 and SL 387 was obtained by Bica et al. (1996). Based on their integrated magnitudes and colours this binary cluster candidate consists of two coeval components with SWB type IVa which corresponds to an age of 200 to 400 Myr. This is not totally consistent with our findings. Though we derived an age for SL 387 which agrees with SWB type IVa, SL 385 is a younger star cluster with an age of 170 $\pm$ 30 Myr which corresponds to SWB type III. This difference might be explained with the use of different aperture sizes: Bica et al. (1996) used a diaphragm size of 40″ which is that large that also bright stars from the companion cluster must have been included. We choose a radius of 27″/2 and thus use a somewhat smaller area from which we derived the CMDs. We cannot rule out that also our CMDs might be contaminated with stars of the companion cluster, but these should not be bright stars and thus will not affect our age determination.

Vallenari et al. (1998) derived ages for this cluster pair by comparing isochrones of the Padua group (e.g. Bertelli et al. [1994] with CMDs. While we applied a statistical field star subtraction they concentrate on all stars which can be found in the inner central area with 27″ radius. In addition they assume the reddening of $E_{B-V} = 0.15$ mag taken from Schwering & Israel (1991). Since small scale variations cannot be resolved by these reddening maps we derived $E_{M-T1}$ from isochrones fits. Vallenari’s et al. (1998) findings for SL 385 are in good agreement with our results. Vallenari’s et al. (1998) data are $\approx 2$ magnitudes deeper than ours. For SL 387 they find an age of $\approx 500$ Myr, while we can only derive a lower limit of 250 Myr. Both data sets are affected by crowding and Vallenari et al. (1998) discuss the adverse effects of field star contamination on their age determination. A definitive age determination for this cluster will have to be postponed until better data are available.

4.3. NGC 1894 & SL 341:

The CMDs for the cluster pair NGC 1894 & SL 341 are shown in Fig. 9. We consider all stars within a radius of 140 pixels (corresponding to 37″/8 or 9.2 pc) for NGC 1894, and 110 pixels (corresponding to 29″/7 or 7.2 pc) for SL 341, respectively, as likely cluster members. Again, both large and small dots represent all stars located inside the chosen region while only the large data points remain after statistical field star subtraction.

The CMD of NGC 1894 shows a pronounced main sequence (average seeing 1″/1) and some red and blue supergiants around $V \approx 14.5$ mag. Nearly all red clump stars and red giants vanish after field star subtraction (small dots). Fitting isochrones to the apparent main sequence turnoff at $V \approx 16$ mag and to the brightest supergiants results in an age of 50 Myr (solid line) and 63 Myr (dotted line). Three blue supergiants below the two isochrones can be seen in the CMD (at $V \approx 16$ mag). A 100 Myr isochrone would fit these three data points but would not fit to the main sequence turnoff or the brighter cluster giants. Two of the stars in question are located more than 29″/7 away from the cluster’s centre, thus it is likely that they belong to the surrounding field star population and remain in the CMD due to somewhat imperfect statistics. Most of the brightest stars are located inside a radius of 21″/6, thus we are confident that they belong to the star cluster.

SL 341 is a much smaller star cluster. Its CMD shows a bright but sparse main sequence with a turnoff at $V \approx 16$ mag, and only few red supergiants at $V \approx 16$. Most red giants and He-core-burning stars are rejected by the field star subtraction. Isochrones with ages of 50 Myr (solid line) and 63 Myr (dotted line) give a good fit to the main sequence turnoff and to the bluest of the candidate red supergiants.

We adopt an age of $55 \pm 5$ Myr for both clusters. Thus, the components of this pair may be considered coeval.

For all isochrone fits we determined a reddening of $E_{B-V} = 0.1$ mag which is in agreement with the reddening maps from Burstein & Heiles (1982) or Schwering & Israel (1991).

4.3.1. Previous age determinations:

Only for NGC 1894 a previous age determination can be found in Bica et al. (1996). Using an aperture size of 34″ which is slightly smaller that our adopted radius (37″/8) Bica et al. (1996) found that NGC 1894 belongs to SWB type II. This corresponds to an age of 30 – 70 Myr which is in agreement with our findings.

It was not attempted previously to determine the age of the companion cluster SL 341.

A summary of previous age determinations derived from the various methods and ours is presented in Table 4.
Fig. 9. CMD of the binary cluster candidate NGC 1894 and SL 341. All stars that are located inside a circular area with a radius of 37.8′′ (NGC 1894) or 29.7′′ (SL 341) have been considered (large and small dots). Only the large data points remain after field star subtraction. As can be seen, the red clump and the red giants belong to the field star population. Overplotted on the CMDs are the best fitting isochrones. Both the 50 Myr and the 63 Myr isochrone give good fits to the clusters’ CMDs, indicating that both clusters have similar ages.

Table 4. Comparison of earlier age determinations and our results

| cluster     | age [Myr] | reference               |
|-------------|-----------|-------------------------|
| NGC 1971    | 30−70     | Bica et al. (1996)      |
|             | 63        | this work               |
| NGC 1972    | 30−70     | Bica et al. (1996)      |
|             | 40±10     | this work               |
| NGC 1969    | 70−200    | Bica et al. (1996)      |
|             | 65±15     | this work               |
| SL 385      | 200−400   | Bica et al. (1996)      |
|             | 150±50    | Vallenari et al. (1998) |
|             | 170±30    | this work               |
| SL 387      | 200−400   | Bica et al. (1996)      |
|             | 500±100   | Vallenari et al. (1998) |
|             | ≥250      | this work               |
| NGC 1894    | 30−70     | Bica et al. (1996)      |
|             | 55±5      | this work               |
| SL 341      | 55±5      | this work               |

4.4. The surrounding field populations:

Both the triple cluster NGC 1971, NGC 1972 and NGC 1969, and the cluster pair SL 385 and SL 387 are located in the dense field of the LMC bar which consists of a mixture of populations of different ages. The cluster pair NGC 1894 & SL 341 are located at the south-western rim of the bar where the surrounding field is less dense but shows a density gradient towards the bar (see Figs. 5 and 6). The CMDs of the eastern and the western fields are shown in Fig. 10.

In each CMD a blue main sequence and blue and red supergiants, which represent the youngest field population, can be seen. The intermediate age population is represented through red giants and the pronounced red clump. We are not able to distinguish between distinct young populations, but the few overplotted isochrones indicate an age range supported by corresponding supergiants.

The eastern field around the three clusters seems to be as young as 40 Myr (dotted isochrone) which corresponds to the young age of NGC 1972. The youngest field population is part of LH 59. Also the 80 Myr isochrone (short dashed line, corresponding to the age of NGC 1969, the oldest of the three clusters) is supported by a large amount of red and blue supergiants and gives a good fit to the main sequence turnoff. The stellar density between 80 Myr and 200 Myr (long dashed line) seems to be lower which indicates a possible decrease in the field star formation rate. Along the 200 Myr isochrone and below the stellar density of the He-core burning giants is increased, indicating enhanced star formation.

The brightest main sequence stars in the middle CMD of Fig. 10 indicate that the field surrounding the cluster pair SL 385 and SL 387 could be as young as 13 Myr (dotted isochrone). The 63 Myr (short dashed line) and the 100 Myr
Fig. 10. Left: CMD of the field populations surrounding the triple cluster candidate NGC 1971, NGC 1972 and NGC 1969. Stars with \( T_2 \geq 15 \text{ mag} \) are represented as smaller dots to keep the isochrones recognizable. The field populations comprise a mixture of ages: the blue main sequence represent the youngest populations that are part of the association LH 59, the red giants and the pronounced red clump belong to the intermediate age populations. Middle: CMD of the field surrounding the cluster pair SL 385 & SL 387. The youngest field population has an age of 13 Myr and thus seems to be younger than the field surrounding NGC 1971. Right: CMD of the field around the double cluster NGC 1894 & SL 341. For all isochrones we adopt a reddening of \( E_{B-V} = 0.05 \text{ mag} \) which is lower than the value adopted for the cluster pair. The brightest stars are fitted by a 16 Myr isochrone. It seems that the western fields are younger than the field around the triple cluster candidate

(long dashed line) isochrones are supported by blue and red supergiants. Below 100 Myr star formation rate seems to be decreased. Star density along the subgiant branch is again increased along and below the 200 Myr isochrone (solid line).

The right CMD of Fig. 10 presents the field populations around the coeval clusters NGC 1894 & SL 341. Fitting the brightest main sequence stars and supergiants results in an age of 16 Myr (solid line). We see a large amount of supergiants at \( V \approx 14 - 15 \text{ mag} \) between the 32 Myr (dotted line) and 63 Myr (short dashed line) isochrone, indicating increased star formation during which also the cluster pair was formed. Also the 100 Myr isochrone (long dashed line) is supported by a number of giants. Below the 63 Myr isochrone the density along the subgiant branch is lower, but increases again along and below the 160 Myr isochrone (bottom solid line).

From our isochrone fitting we find that the western fields are younger (13 and 16 Myr) than the eastern field (40 Myr). This is consistent with the age gradient found by Bica et al. (1996) for the LMC bar.

5. The probability of close encounters

The probability of tidal capture of one cluster by another one is small (Bhatia et al. 1991), but van den Bergh (1996) argues that it becomes more probable in dwarf galaxies like the Magellanic Clouds with small velocity dispersion of the cluster systems. In that case the clusters of a later formed pair do not need to be coeval. Vallenari et al. (1998) estimated a cluster encounter rate of \( dN/dt \sim 1 \cdot 10^{-9} \text{ yr}^{-1} \) in the LMC which makes a capture between young clusters unlikely (for the definition of \( dN/dt \) see below). However, they argue that an interaction between LMC and SMC, which was suggested in Bica et al. (1996), might also increase the encounter rate. Bica et al. (1996) found a concentration of older clusters (SWB type III – V, corresponding to ages of 70 – 2000 Myr) towards the western end of the LMC bar and argue that this may be the result of an LMC – SMC interaction \( \approx 300 \text{ Myr} \) ago. If indeed such an interaction would increase the cluster encounter rate, we would also expect a concentration of binary cluster candidates towards the western part of the bar. We do not see such a concentration in Bhatia et al. (1991, their Fig. 5). We re-determine the encounter rate in the LMC bar using the new, extended catalogue of LMC clusters and associations from Bica et al. (1999). Following Lee et al. (1995):

\[
\frac{dN}{dt} = \frac{1}{2} \frac{N - 1}{V} \cdot \sigma \cdot v
\]

where \( N \) is the number of clusters, \( V \) denotes the volume of the galaxy, \( \sigma = \pi R^2 \) is the geometric cross section of a cluster with radius \( R \), and \( v \) is the velocity dispersion of the cluster system of that galaxy. For the LMC bar we assume a cylinder with a length of 3° 05′ corresponding to \( \approx 2700 \text{ pc} \) and a width of 40′ 5
or 590 pc. Typical cluster radii are about 10 pc. For the velocity dispersion of the cluster system we adopt 15 km s\(^{-1}\) as quoted in Vallenari et al. (1998). In Fig. 11 we plotted all clusters from the Bica et al. (1999)-catalogue. The clusters which are located in the bar region are marked with open circles. 484 clusters are situated in our selected area, leading to an encounter rate of \(\frac{dN}{dt} \approx 2 \cdot (10^9 \text{yr})^{-1}\).

Outside of the bar region 3605 star clusters can be found. Assuming a disk-like shape of the LMC with a radius of 6° corresponding to 5300 pc and a depth of 400 pc (Hughes et al. 1991) we get an encounter rate of \(\frac{dN}{dt} \approx 3 \cdot (10^{10} \text{yr})^{-1}\). Indeed the encounter rate is increased in the LMC bar by a factor of 10. However, only very few encounters would result in tidal capture. The probability of tidal capture will depend strongly on the velocities of the two clusters with respect to each other, the angle of incidence, whether a prograde or retrograde encounter takes place, whether sufficiently angular momentum can be transferred, and whether the clusters are sufficiently massive to survive the encounter. It seems unlikely that a significant number of young pairs may have formed through tidal capture.

### 6. Summary and conclusions

We investigated the stellar densities in and around the triple cluster NGC 1971, NGC 1972, and NGC 1969. The isopleths do not show connections between the clusters, but reveal the distortion of NGC 1971 towards the other two clusters. NGC 1969 is much more extended than can be seen from short exposed optical images. Furthermore we see a clumpy structure on the stellar density map. Whether this is due to hierarchical
stellar clustering (see text below) or due to background fluctuations cannot be clearly said.

Comparing isochrones based on the Geneva models (Schaerer et al. 1993) with the CMDs of each star cluster we find the following ages: $63 \pm 10$ Myr for NGC 1971, $40 \pm 10$ Myr for NGC 1972, and $65 \pm 15$ Myr for NGC 1969.

Within the errors all three clusters are similar in age and may have been formed in the same GMC. The slight age differences suggest that cluster formation occurred in several episodes, with NGC 1969 as the oldest of the triple cluster which might have triggered the formation of the other two clusters, and NGC 1972 as the smallest and youngest object. Similar evidence for multiple episodes of cluster formation separated by a few tens of Myr have also been observed in 30 Doradus (Grebel & Chu 2000). The triple cluster can be seen as an example of hierarchical stellar clustering (Elmegreen et al. 1999 and references therein): All three clusters are embedded in the larger association LH 59. The youngest field star population is part of LH 59 and has an age of 40 to 80 Myr which corresponds to the ages for the three clusters. The clumpy structure of NGC 1969 reveals stellar clustering on smaller scales. Whether the star clusters are physically connected or not cannot be clearly decided. Both NGC 1971 and 1969 show somewhat distorted isophotes which might indicate a possible interaction, but this is highly uncertain. A thorough radial velocity study for binary and multiple cluster candidates would be helpful.

Both NGC 1894 and SL 341 reveal an elliptical shape on the stellar density map. A significant enhancement between the clusters was not found. A density gradient can be seen in Fig. 3 in direction of the LMC bar. Whether the elliptical shape of the two clusters is due to interaction or is a peculiarity that is found for a large amount of single clusters in the LMC (Goodwin 1997) is unclear.

Fitting isochrones to the CMDs we find that the components of this cluster pair are coeval within the measurement accuracy with an age of $55 \pm 5$ Myr. It is likely that both clusters have formed from the same GMC. Whether they have or had some interaction cannot be decided, since most LMC clusters show larger ellipticities than clusters of the Milky Way.

The models of both Fujimoto & Kumai (1997) and Theis (1998) (see Sect. 1) provide possible formation scenarios for the triple cluster NGC 1971, NGC 1972 & NGC 1969 and the cluster pair NGC 1894 & SL 341.

The star density map of SL 385 & SL 387 shows an enhancement between the two clusters which connects the components of this binary cluster candidate. The enhancement is $2\sigma$ above the mean of the surrounding field. However, both clusters have a projected distance of $45''/6$ corresponding to 11.1 pc and an extension of $\approx 27''/2$ or 9.2 pc radius. It is likely that the isophotes of the clusters are overlapping even if the clusters may have different distances along the line of sight, e.g. both clusters may appear as a pair only due to chance superposition. Based on deeper data, Leon et al. (1995) suggest the presence of two partially overlapping tidal tails distinguishable by their different stellar populations, which are indicative of a possible encounter between these two clusters of different ages.

Based on isochrone fitting to the CMDs we derived an age of $170 \pm 30$ Myr for SL 385, while only a lower age limit of 250 Myr could be found for SL 387. If we adopt the ages estimated by Vallenari et al. (1998), then the age difference is $\approx 350$ Myr, far above the maximum life time of protocluster gas clouds suggested by Fujimoto & Kumai (1997).

We calculated cluster encounter rates for the bar and the disk of the LMC. We found the cluster encounter rate to be increased by a factor of 10 in the dense, cluster-rich LMC bar as compared to the disk of the LMC, though the rate is still very low (2 encounters per Gyr!). Since additional conditions such as sufficient angular momentum loss must be fulfilled for a tidal capture of one cluster by another during an encounter, this seems an unlikely formation scenario for the formation of binary clusters. Obtaining radial velocities for a large number of stars in cluster pairs, in their potential tidal tails, and in the surrounding field population would help to evaluate cluster internal and external dynamics and to rule out or confirm the occurrence of interactions.

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