Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY LETTERS

Mon. Not. R. Astron. Soc. **416,** L89–L93 (2011) doi:10.1111/j.1745-3933.2011.01105.x

New candidate intermediate-age star clusters in the Small Magellanic Cloud

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Accepted 2011 June 27. Received 2011 June 27; in original form 2011 June 10

ABSTRACT

We present the results on the age and metallicity estimates of nine Small Magellanic Cloud (SMC) clusters (AM 3, HW 31, 40, 41, 42, 59, 63, L91 and NGC 339) obtained from CCD Washington CT_1T_2 photometry. We confirm AM 3 and NGC 339 as intermediate-age and metal-poor clusters, and report for the first time that the remaining seven clusters are also intermediate-age or old clusters ($t \sim$ 4.3–9.3 Gyr), which represents an increase of $\gtrsim$60 per cent of the total known intermediate-age/old cluster population in the SMC. The studied clusters have metal contents ranging from intermediate metal-poor ([Fe/H] ≈ -0.7 dex) down to metal-poor ([Fe/H] ≈ -1.3 dex) values.

Key words: techniques: photometric – galaxies: individual: SMC – Magellanic Clouds – galaxies: star clusters.

1 INTRODUCTION

The issue about the existence of old star clusters in the Small Magellanic Cloud (SMC) has always aroused an enormous interest. An updated census of SMC star clusters with well estimated ages larger than 1 Gyr has recently been provided by Piatti et al. (2011, see their table 19). From the 43 clusters listed by them, only 11 could actually be considered intermediate age or old (age $\gtrsim$5 Gyr). Despite the different campaigns carried out until the present searching old star clusters in the SMC, unfortunately new candidates have not been identified. These results would appear not only to show that the task of finding more old star clusters in the SMC is arduous, but also it would appear a venture hardly to reach success. The amazing scarce amount of old SMC star clusters results even more noticeable when comparing it with the 456 star clusters catalogued in the SMC (Bonatto & Bica 2010), thus representing less than 3 per cent of the SMC star cluster population.

Based on these handfuls of known intermediate-age/old clusters, recent studies have appeared in the literature with a view which improves our knowledge about the formation and chemical evolution of the SMC. For example, the estimates of age and metallicity of old clusters have helped us in the study about the SMC age–metallicity relation (AMR; Piatti et al. 2007; Parisi et al. 2009), about its hierarchical structure (Bonatto & Bica 2010), about the cluster age distribution (Piatti et al. 2011), etc., among others. On the other hand, from a theoretical point of view, Tsujimoto & Bekki (2010) have just reported evidence that a major merger is imprinted in the AMR as a dip in [Fe/H], occurred ~7.5 Gyr ago. Therefore, it is of great significance to know whether these are the only intermediate-age/old SMC clusters, in order to make up a strong image about the formation and chemical evolution of the galaxy.

In this Letter we identified seven new possible candidate intermediate-age/old star clusters in the SMC. Since the new candidate sample represents an increase of $\gtrsim$60 per cent of the intermediate-age/old star cluster population, it would pose new challenges about our knowledge about the AMR, the cluster formation and disruption rates, about the infant mortality phenomenon, etc. The data handling from which we found these new candidate intermediate-age/old clusters is described in Section 2. Section 3 deals with the resultant cluster colour–magnitude diagrams (CMDs) and the cluster properties, whereas Section 4 summarizes our results.

2 DATA HANDLING

In our previous series of studies about SMC clusters we have used the CT_1 Washington photometric system (Canterna 1976; Geisler 1996) whose ability to estimate ages and metallicities of star clusters have long been proved (Piatti et al. 2011, and references therein). For those reasons, and in order to keep consistent with our previous studies as well, we performed a search within the National Optical Astronomy Observatory (NOAO) Science Data Management (SDM) Archives[1] looking for Washington photometric data centred on fields towards the SMC. As result, we found images obtained at the Cerro Tololo Inter-American Observatory (CTIO) 4-m Blanco telescope with the Mosaic II camera attached (36 × 36 arcmin^2 field on to a 8K × 8K CCD detector array) of several mostly unstudied SMC star clusters. Table 1 summarizes a selection of the images'

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[1] http://www.noao.edu/sdm/archives.php

Table 1. Candidate intermediate-age/old star clusters in the SMC.

Star cluster[a]	α_{2000} ($^{\rm h\,m\,s}$)	δ_{2000} (° ′ ″)	l (°)	b (°)	Date	Exposure $C\,R\,I$ (s)	Airmass $C\,R\,I$	Seeing $C\,R\,I$ (arcsec)
AM 3	23 48 59	−72 56 43	309.17	−43.41	2008 December 18	1500 300 300	1.549 1.518 1.534	1.1 1.1 1.1
HW 31	00 55 33	−74 03 49	302.54	−43.06	2008 December 19	1500 300 300	1.495 1.476 1.485	1.2 1.0 0.8
HW 40	01 00 25	−71 17 41	301.89	−45.81	2008 December 19	1500 300 300	1.510 1.482 1.496	1.2 0.8 0.7
HW 41	01 00 35	−71 27 39	301.89	−45.64	2008 December 19	1500 300 300	1.510 1.482 1.496	1.2 0.8 0.7
HW 42	01 01 08	−74 04 25	302.02	−43.03	2008 December 19	1500 300 300	1.495 1.476 1.485	1.2 1.0 0.8
HW 59	01 08 54	−73 14 30	301.17	−43.83	2008 December 20	1200 300 300	1.569 1.541 1.555	1.3 1.1 0.9
HW 63	01 10 13	−73 12 33	301.05	−43.85	2008 December 20	1200 300 300	1.569 1.541 1.555	1.3 1.1 0.9
L91	01 12 51	−73 07 10	300.77	−43.91	2008 December 20	1200 300 300	1.569 1.541 1.555	1.3 1.1 0.9
NGC 339	00 57 42	−74 28 22	302.35	−42.65	2008 December 19	1500 300 300	1.495 1.476 1.485	1.2 1.0 0.8

[a]Cluster identifications are from Madore & Arp (1979, AM), Hodge & Wright (1974, HW) and Lindsay (1958, L).

log with filters, exposure times, airmasses and seeing estimates. As far as we are aware, none of the clusters listed in Table 1 does have CT_1T_2 photometry published previously. Note that the R and I filters have significantly higher throughputs as compared with the standard Washington T_1 and T_2 filters so that R and I magnitudes can be accurately transformed to yield T_1 and T_2 magnitudes (Geisler 1996).

The data reduction followed the procedures documented by the NOAO Deep Wide Field Survey team (Jannuzi, Claver & Valdes 2003) and utilized the MSCRED package in IRAF.[2] We performed overscan, trimming and cross-talk corrections, bias subtraction, obtained an updated world coordinate system (WCS) data base, flattened all data images, etc., once the calibration frames (zeros, sky- and dome flats, etc.) were properly combined. Nearly 90 independent measures of standard stars from the list of Geisler (1996) were also derived per filter for each night in order to secure the transformation from the instrumental to the standard system. We solved the transformation equations with the FITPARAMS task in IRAF and found mean colour terms of -0.090 ± 0.003 in C, -0.020 ± 0.001 in T_1 (R) and 0.060 ± 0.004 in T_2 (I), while typical airmass coefficients resulted in 0.31, 0.09 and 0.06 for C, T_1 and T_2, respectively. The nightly rms errors from the transformation to the standard system were 0.021, 0.023 and 0.017 mag for C, T_1 and T_2, respectively, indicating these nights were of excellent photometric quality.

The stellar photometry was performed using the star finding and point spread function (PSF) fitting routines in the DAOPHOT/ALLSTAR suite of programs (Stetson, Davis & Crabtree 1990). For each frame, a quadratically varying PSF was derived by fitting ∼960 stars, once the neighbours were eliminated using a preliminary PSF derived from the brightest, least contaminated ∼240 stars. Both groups of PSF stars were interactively selected. We then used the ALLSTAR program to apply the resulting PSF to the identified stellar objects and to create a subtracted image which was used to find and measure magnitudes of additional fainter stars. This procedure was repeated three times for each frame. Finally, we standardized the resulting instrumental magnitudes and combined all the independent measurements using the stand-alone DAOMATCH and DAOMASTER programs, kindly provided by Peter Stetson. The final information gathered for each cluster consists of a running number per star, of the x and y coordinates, of the measured T_1 magnitudes and $C - T_1$ and $T_1 - T_2$ colours and of the observational errors $\sigma(T_1)$, $\sigma(C - T_1)$ and $\sigma(T_1 - T_2)$. The T_1 magnitude and $C - T_1$ and $T_1 - T_2$ colour errors provided by DAOPHOT II are shown in Fig. 1, where we only plotted the errors for stars measured in the central region (r = 80 arcsec) of NGC 339 – the most populated cluster of the sample – to emphasize crowding effects.

[2] IRAF is distributed by the NOAO, which is operated by the Association of Universities for Research in Astronomy, Inc., under contract with the National Science Foundation.

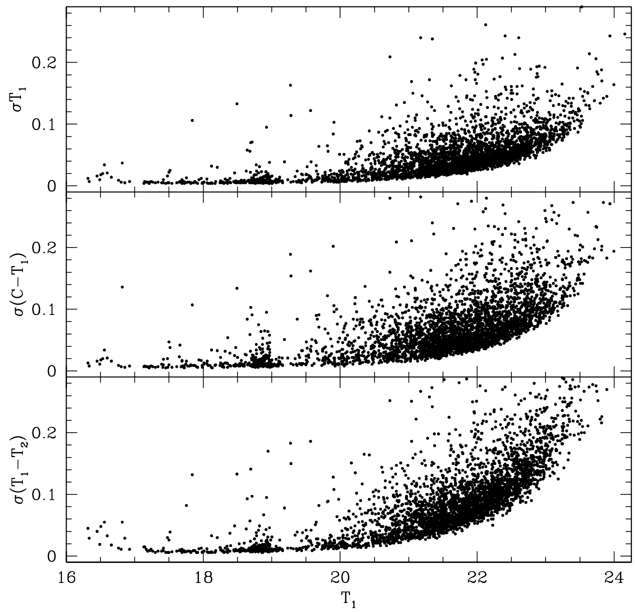

Figure 1. Magnitude and colour photometric errors as a function of T_1 for a 80 arcsec circular extraction around NGC 339.

3 DATA ANALYSIS

We started by estimating the clusters' geometrical centres to obtain circular extracted CMDs where the fiducial features of the clusters could be clearly seen. The cluster centres were estimated using the NGAUSSFIT task within the STSDAS/IRAF package. We then constructed the cluster radial profiles depicted in Fig. 2, which served us to adopt representative cluster radii to perform circular extractions (see column 2 of Table 2). Using equal area field CMDs as reference, we statistically cleaned the cluster CMDs from field contamination using a procedure based on the precepts outlined by Bonatto & Bica (2007). The selected field areas are rings around the cluster centres with internal radii four times those of the respective cluster radii. Finally, using the T_1 versus $C - T_1$ and T_1 versus $T_1 - T_2$ CMDs and the $C - T_1$ versus $T_1 - T_2$ colour–colour diagram cleaned from field star contamination obtained, we supplementarily applied the criteria defined by Clariá & lapasset (1986) to evaluate

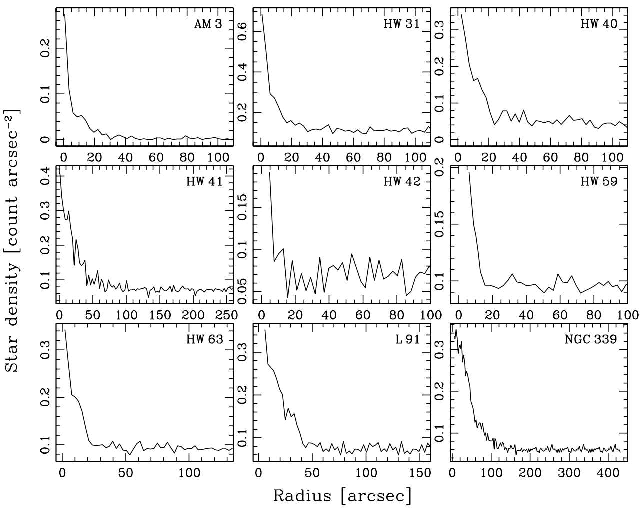

Figure 2. Density profiles for the selected clusters.

the membership status of the measured stars, which require that the location of a star in the three diagrams corresponds to the same evolutionary stage. Although we carried out an overall careful task of field star cleaning, the resultant CMDs do not contain only cluster stars due to the unavoidable residuals, but strongly highlight the main cluster features. Fig. 3 shows the observed cluster CMDs (top panels), the respective equal area star field CMDs (middle panels) and the resultant cleaned cluster CMDs (bottom panels).

We are primarily interested in determining the age and metal abundance of each cluster in our sample. In order to maintain consistency, we have utilized the same techniques to measure these quantities as in our previous papers on SMC clusters (Piatti et al. 2011, and references therein). First, we adopt a distance modulus of $(m - M)_o = 18.90 \pm 0.10$ recently reported by Glatt, Grebel & Koch (2010). The reddening values are taken from the Burstein & Heiles (1982), Schlegel, Finkbeiner & Davis (1998) and Haschke, Grebel & Duffau (2011) extinction maps, adopting weighted average values (see Table 2). As can be seen, both the small reddening values as well as their errors suggest that no differential reddenings would affect the clusters.

The ages were calculated by determining the difference in T_1 magnitude between the red clump (RC) and the main sequence turnoff (MSTO) from the cluster CMDs and then using equation (4) of Geisler et al. (1997) to obtain the ages. Note that this age measurement technique does not require absolute photometry. The derived δT_1 differences are listed in Table 2; their uncertainties $\sigma(\delta T_1)$ were estimated by considering the photometric errors at the RC and MSTO T_1 magnitudes (see Fig. 1 and columns 4 and 5 of Table 2) and/or the intrinsic dispersion in the CMDs. We notice that when the number of stars is small, the δT_1 value should be used with caution. The computed cluster ages are listed in column 7 of Table 2, and their errors come from the propagation of $\sigma(\delta T_1)$ through equation (4) of Geisler et al. As can be seen, although the age errors are slightly large, the selected clusters are clearly older than 4 Gyr and are thus new discovered candidate intermediate-age/old clusters in the SMC. Fortunately, AM 3 (age = 5.5 ± 1.5 Gyr; Da Costa 1999) and NGC 339 (age = 4.0 ± 1.5 Gyr; Da Costa & Hatzidimitriou 1998) served us as age control clusters, thus confirming that we are in the same age scale of Piatti et al. (2011, their table 19). On the other hand, Glatt et al. (2010) have recently studied HW 31, 40, 41 and 42, assuming that they are clusters younger than 1 Gyr. As they mentioned, this could be due to their limited photometric depth and/or biased field star contamination cleaning.

The metallicities have been estimated by comparing the cluster red giant branches (RGBs) with the standard fiducial globular cluster RGBs from Geisler & Sarajedini (1999). The scattering of the data in the $[M_{T_1}, (C - T_1)_o]$ plane, with the different iso-abundance lines superimposed, was used to assign the random errors to the metallicities. This derived metallicity was then corrected for age effects via the prescription given in Geisler et al. (2003). We note that metallicities determined in this way have been found to be in good agreement with those derived from comparison to appropriate theoretical isochrones (e.g. Piatti et al. 2011). The resulting metal abundances are listed in the last column of Table 2, where we took into account errors associated with the age correction. Finally, we checked the derived ages by fitting theoretical isochrones of Girardi et al. (2002) to the cluster CMDs. We used isochrones for $Z = 0.001$ and 0.004, since there is none available for $Z = 0.002$, and confirmed the derived cluster ages of Table 2; the average metallicity differences (absolute values) being within 0.1 dex.

Including the clusters listed by Piatti et al. (2011), we have now studied the chemical enrichment of the SMC. We show in Fig. 4 the cluster spatial distribution (left-hand panel) and the AMR (right-hand panel) constructed. Open and filled symbols represent clusters from Piatti et al. and our sample, respectively. We have also overplotted two star formation models for comparison purposes. The solid line represents the bursting star formation history of Pagel & Tautvaišienė (1998), whereas the dashed line depicts a simple closed system with continuous star formation under the assumption of chemical homogeneity (Da Costa & Hatzidimitriou 1998). The appearance of the AMR still supports the bursting star formation model as the most probable paradigm to describe the SMC.

Table 2. Fundamental parameters of SMC clusters.

Name	r (arcsec)	$\langle E(B-V)\rangle$ (mag)	T_1 (MSTO) (mag)	T_1 (RC) (mag)	δT_1 (mag)	Age (Gyr)	[Fe/H][a]
AM 3	30 ± 5	0.025 ± 0.005	21.80 ± 0.10	19.10 ± 0.05	2.70 ± 0.15	6.0 ± 1.0	−1.25 ± 0.25
HW 31	20 ± 5	0.030 ± 0.010	21.50 ± 0.10	19.00 ± 0.05	2.50 ± 0.15	4.8 ± 1.0	−0.90 ± 0.25
HW 40	20 ± 5	0.060 ± 0.010	21.60 ± 0.10	19.00 ± 0.05	2.60 ± 0.15	5.4 ± 1.0	−1.10 ± 0.25
HW 41	80 ± 20	0.060 ± 0.010	21.70 ± 0.10	19.00 ± 0.05	2.70 ± 0.15	6.0 ± 1.0	−1.00 ± 0.25
HW 42	15 ± 5	0.030 ± 0.010	21.90 ± 0.10	18.80 ± 0.05	3.10 ± 0.15	9.3 ± 1.5	−1.40 ± 0.25
HW 59	15 ± 5	0.040 ± 0.020	21.80 ± 0.10	19.00 ± 0.05	2.80 ± 0.15	6.7 ± 1.1	−1.00 ± 0.25
HW 63	20 ± 10	0.040 ± 0.020	21.80 ± 0.10	19.20 ± 0.05	2.60 ± 0.15	5.4 ± 1.0	−0.70 ± 0.25
L91	40 ± 10	0.040 ± 0.010	21.70 ± 0.10	19.30 ± 0.05	2.40 ± 0.15	4.3 ± 1.0	−0.70 ± 0.25
NGC 339	150 ± 40	0.040 ± 0.010	21.60 ± 0.10	19.00 ± 0.05	2.60 ± 0.15	5.4 ± 1.0	−1.30 ± 0.25

[a]Metallicities were corrected according to fig. 6 of Geisler et al. (2003). See Section 3 for details.

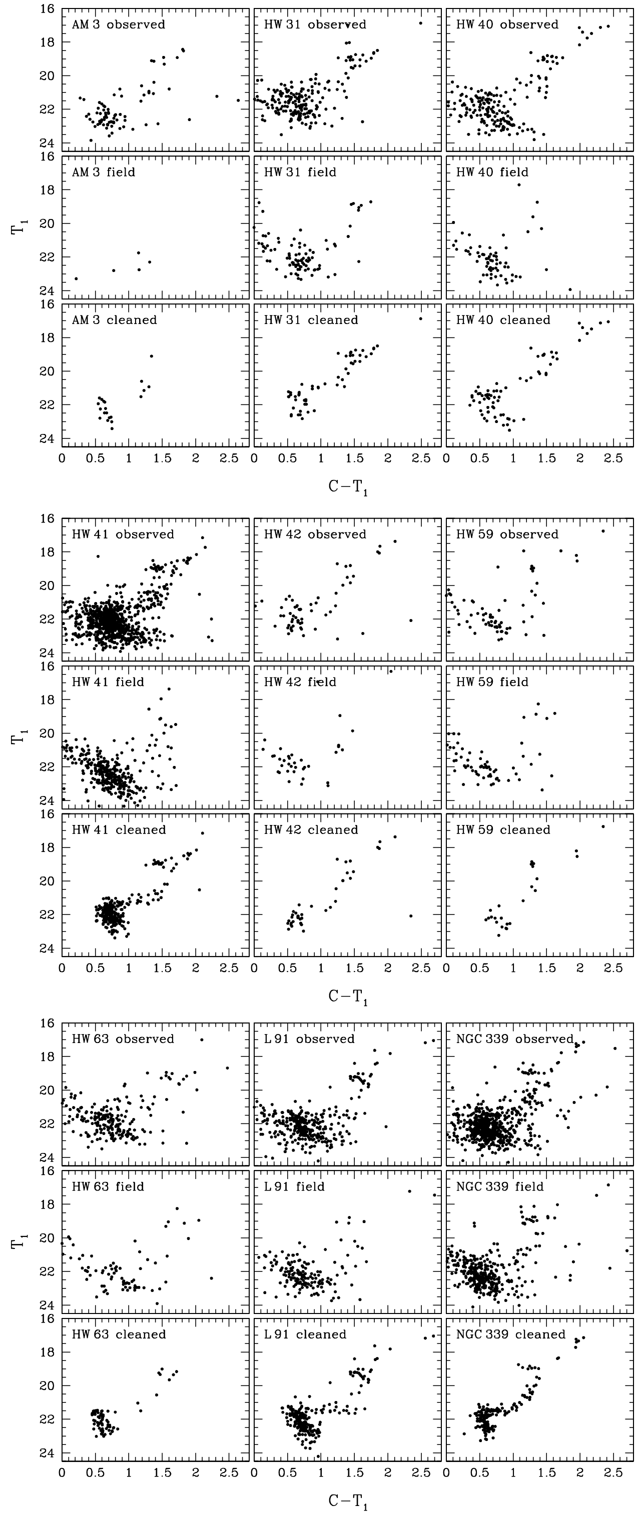

Figure 3. Extracted Washington T_1 versus $C - T_1$ CMDs for stars distributed within the cluster radius (upper), the cluster surrounding field for an equal cluster area (middle) and the cluster cleaned from field contamination (bottom).

However, the metallicity dispersion in the 5–7 Gyr age range suggests another possible burst – first showed by Rich et al. (2000) – in addition to the clear burst of cluster formation at ∼3 Gyr. Much further and more detailed work is needed to clarify and quantify these suggested trends.

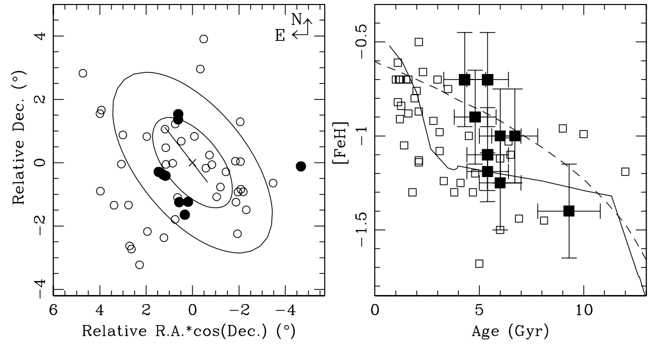

Figure 4. Left-hand panel: the position of the studied clusters (filled circles) in relation to the SMC optical centre (cross). The semimajor axes of the ellipses drawn in the figure have radii of 2° and 4°, respectively. 41 clusters included in Piatti et al.(2011) are also shown as open circles. Right-hand panel: age–metallicity relationship for star clusters in the SMC (see text for details).

4 SUMMARY

In this study we present CCD Washington CT_1T_2 photometry of stars in the field of nine SMC clusters, namely, AM 3, HW 31, 40, 41, 42, 59, 63, L91 and NGC 339, respectively. The analysis of the photometric data leads to the following main conclusions.

(i) To disentangle cluster features from those belonging to their surrounding fields, we applied subtraction procedures to statistically clean the cluster CMDs from field star contamination.

(ii) Using the cleaned cluster (T_1, $C - T_1$) diagrams, we estimated ages and metallicities using the δT_1 index and standard giant branch (SGB) procedure for the Washington system. These CMDs are particularly sensitive for metallicity determinations. The two methods for both age and metallicity determinations are in very good agreement with theoretical isochrone fitting.

(iii) We confirm that AM 3 and NGC 339 belong to the group of intermediate-age/old SMC clusters, and show for the first time that the remaining seven studied clusters are now added to this group, which represents an increase of $\gtrsim$60 per cent of the total known intermediate-age/old cluster population in the SMC.

(iv) The studied clusters have metal contents ranging from intermediate metal-poor ([Fe/H] ≈ -0.7 dex) down to metal-poor ([Fe/H] ≈ -1.3 dex) values. It would be of great interest to re-examine the AMR and the cluster age distribution to the light of this enlarged intermediate-age/old SMC star cluster population.

ACKNOWLEDGMENTS

I greatly appreciate the comments and suggestions raised by the reviewer which helped me to improve the manuscript. This research draws upon data as distributed by the NOAO Science Archive. NOAO is operated by the Association of Universities for Research in Astronomy (AURA), Inc., under a cooperative agreement with the National Science Foundation. This work was partially supported by the Argentinean institutions CONICET and Agencia Nacional de Promoción Científica y Tecnológica (ANPCyT).

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