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PRE-MAIN-SEQUENCE TURN-ON AS A CHRONOMETER FOR YOUNG CLUSTERS: NGC 346 AS A BENCHMARK*

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ABSTRACT

We present a novel approach to deriving the age of very young star clusters, by using the Turn-On (TOn). The TOn is the point in the color-magnitude diagram (CMD) where the pre-main sequence (PMS) joins the main sequence (MS). In the MS luminosity function (LF) of the cluster, the TOn is identified as a peak followed by a dip. We propose that by combining the CMD analysis with the monitoring of the spatial distribution of MS stars it is possible to reliably identify the TOn in extragalactic star-forming regions. Compared to alternative methods, this technique is complementary to the turnoff dating and avoids the systematic biases affecting the PMS phase. We describe the method and its uncertainties and apply it to the star-forming region NGC 346, which has been extensively imaged with the *Hubble Space Telescope* (*HST*). This study extends the LF approach in crowded extragalactic regions and opens the way for future studies with *HST*/WFC3, the *James Webb Space Telescope* and from the ground with adaptive optics.

Key words: galaxies: evolution – galaxies: star clusters: general – Magellanic Clouds – open clusters and associations: individual (NGC 346) – stars: formation – stars: pre-main sequence

1. INTRODUCTION

The main-sequence (MS) turnoff is the most reliable feature for age-dating a star cluster. Nevertheless for very young clusters, with ages of tenths to a few Myr, the identification of the turnoff is usually hampered by the paucity of massive stars.

We propose to take a different point of view, focusing on the Turn-On (TOn), the color-magnitude diagram (CMD) locus where the pre-main sequence (PMS) joins the MS. Although the importance of the TOn has already been emphasized in several papers (e.g., Stauffer 1980; Belikov et al. 1998; Baume et al. 2003; Naylor et al. 2009), its application to dating extragalactic star-forming regions is a new proposition.

In analogy with the turnoff, the TOn properties are directly related to the age of the stellar population, but with evolutionary times much shorter than the corresponding MS times. In fact, from simple stellar evolution arguments, the age of a cluster is equal to the time spent in the PMS phase by its most massive star still in the PMS phase. By definition, this star is at the TOn. Hence, when the intrinsic luminosity of the TOn is detected, it is straightforward to associate it with the age of the cluster.

In the first part of this Letter, we describe how the intrinsic properties of the TOn can be used as a clock. In the second part, we present a new method for applying TOn-related properties to date extragalactic systems. Finally, we apply this method to the largest extragalactic star-forming region, NGC 346, in the Small Magellanic Cloud (SMC).

2. THE PMS TURN-ON

The potential strength of the TOn is apparent from the morphology of isochrones taking both the PMS and MS phases into account. Figure 1(a) shows five isochrones with metallicity $Z = 0.004$, obtained combining the Pisa PMS tracks (Cignoni et al. 2009) with the Padua evolutionary tracks (Fagotto et al. 1994) to cover the entire mass range 0.45–120 $M_\odot$. For all ages younger than 15 Myr, the isochrone portion just before the zero-age main sequence (ZAMS) has a hook and then is significantly flatter than the ZAMS. The TOn is at the vertex of the hook, quite easy to recognize.

To test if/how the TOn can be useful as a cosmo-chronometer, we simulated synthetic simple stellar populations (SSPs), using the tracks quoted above. As an example, we describe the case with metallicity $Z = 0.004$, burst duration 1 Myr, Salpeter's initial mass function (IMF), and no binaries. To guarantee statistically significant tests, extensive theoretical simulations have been performed with a number of synthetic stars up to 1×10^6.

Panels (b)–(f) in Figure 1 show the luminosity functions (LFs), binned in 0.2 magnitude bins and scaled to the total number of stars, of synthetic SSPs (open histograms) corresponding to the isochrones of panel (a). A reference synthetic zero-age population, which is artificially built without[8] PMS stars (gray filled histogram), is also shown. In the LF without PMS, the only valuable feature is a mild peak around $M_V \approx 2$, consequence of an inflection in the derivative of the mass–M_V relation in MS stellar models around $m = 2\,M_\odot$. By contrast, when the evolution starts from the PMS phase, the corresponding LFs develop an additional strong peak followed by a dip. Peak and dip reflect respectively the steep dependence of stellar

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[8] That is, stars are born directly on the ZAMS.

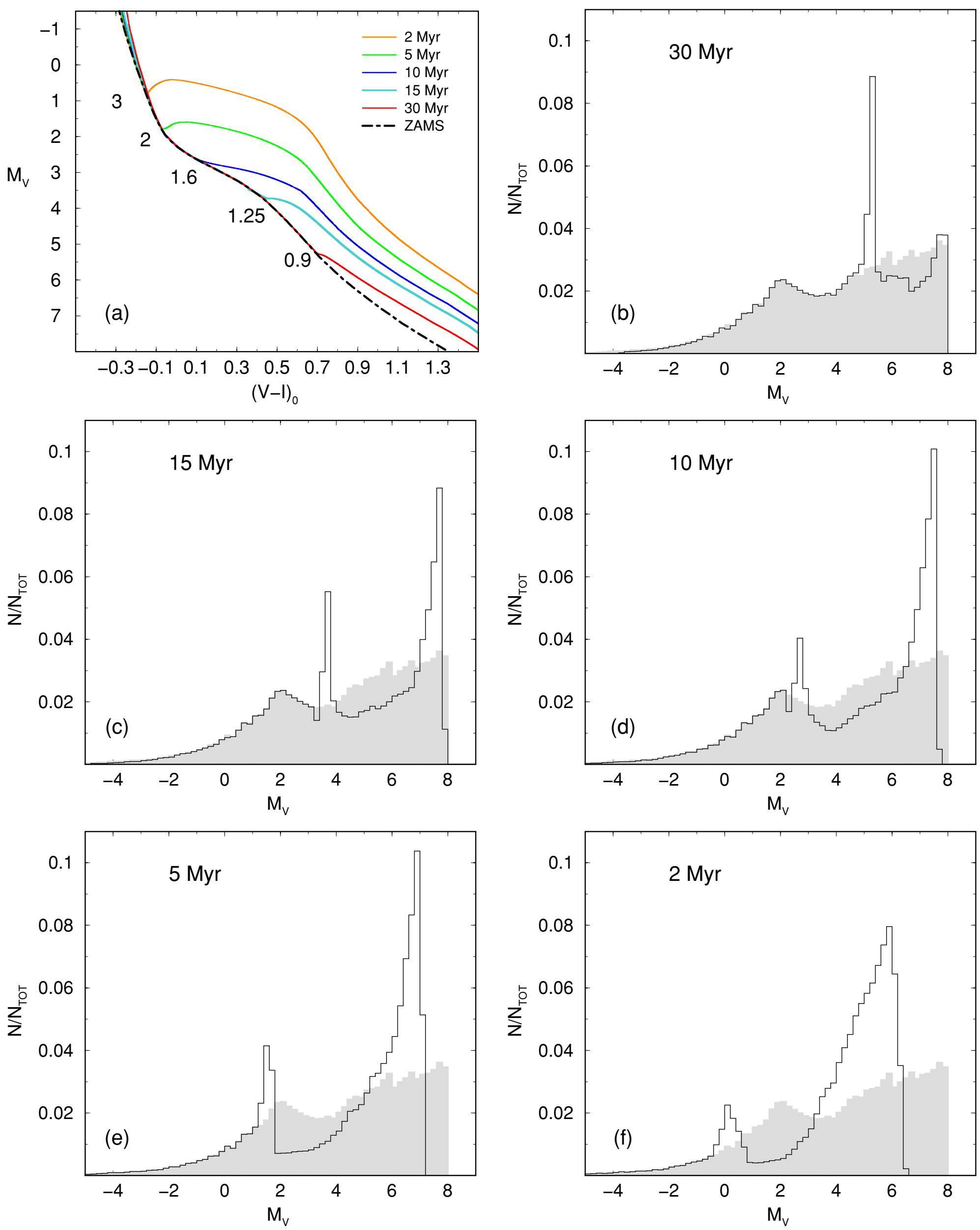

Figure 1. Panel (a): combined PMS and MS isochrones for the labeled ages. The TOn is at the discontinuity where the PMS joins the MS (e.g., at $(V-I)_0 = -0.15$ and $M_V = 0.85$ for the 2 Myr case). The numbers on the left give the mass of the TOn star of each isochrone. Panels (b)–(f): normalized LFs for synthetic SSPs of the labeled age (see the text for details).

mass on M_V near the TOn (see also the discussion in Piskunov et al. 2004) and the following flattening below the TOn (caused by the short evolutionary timescale of the PMS phase compared to the MS). After the dip, the shape of the LF mimics the IMF.

The LFs in Figure 1 indicate the importance of both features, peak and dip, to infer the cluster age: the older the age, the fainter the LF TOn peak and the corresponding dip. On the other hand, for the explored range of ages the magnitude of the MS peak is fairly constant ($M_V \approx 2$), being locked to the (much longer) MS evolutionary times. Through a polynomial fit to the models, theory provides a useful relation between age (τ) of the SSP and the magnitude M_V of the TOn in the range 2–100 Myr:

$$\tau(\text{Myr}) = \sum_{j=0,5} a_j \times (M_V)^j. \quad (1)$$

In turn:

$$M_V = \sum_{j=0,5} b_j \times \{\log[\tau(\text{Myr})]\}^j. \quad (2)$$

Once the bin width of the LF is chosen, Equation (1) (whose coefficients are given in Table 1) gives also the intrinsic uncertainty on the age. Assuming 0.2 mag wide bins, the minimum uncertainty is about 0.6 Myr at 3 Myr, 1.3 Myr at 20 Myr, 2.5 Myr at 30 Myr, and 6 Myr at 50 Myr. The TOn formula is deliberately limited to populations older than 2 Myr, since for younger ages the current PMS models are still extremely uncertain (see Baraffe et al. 2002, for a discussion).

Although attractive, the TOn dating method should be used with caution. When we compare the observed and theoretical LFs, it is important to evaluate the following uncertainties.

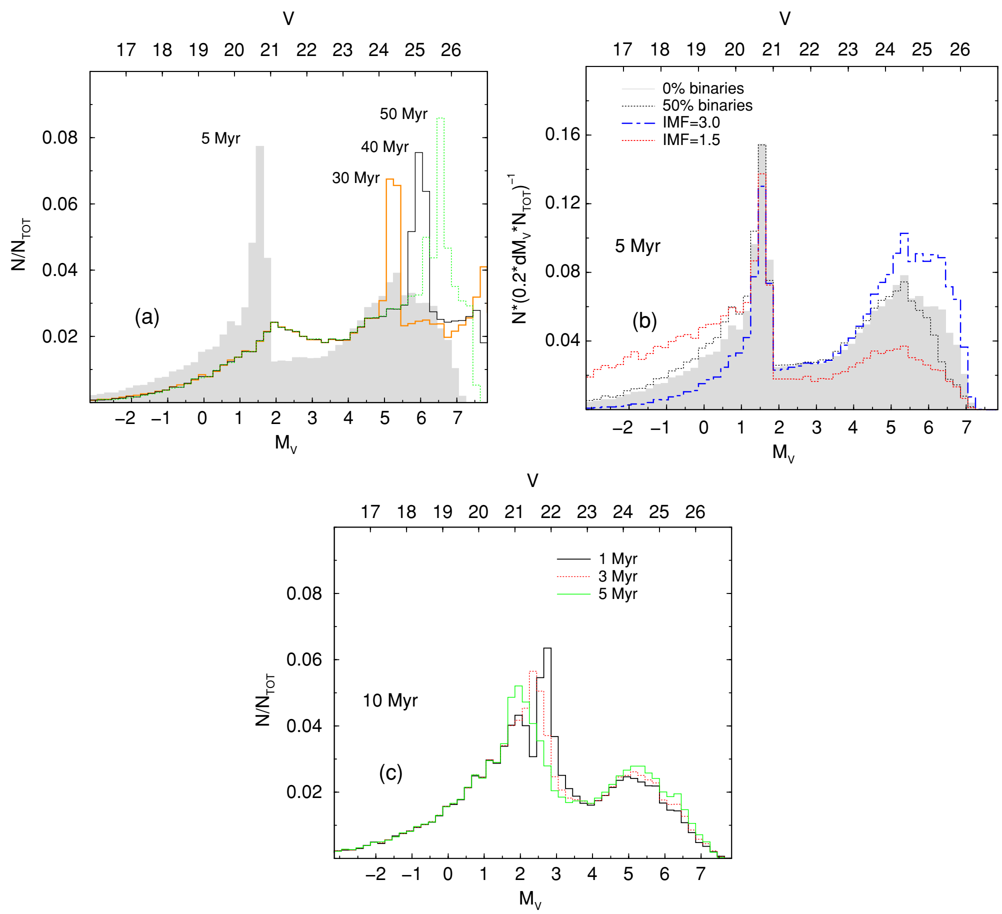

Figure 2. Panel (a): effect of incompleteness and photometric errors on the LFs for the labeled ages. All LFs are normalized to the total number of stars. Panel (b): effect of different IMFs and binary fractions on the 5 Myr LF. The shadowed histogram is the same as the reference 5 Myr case of panel (a). Panel (c): normalized LFs for a 10 Myr cluster with the labeled duration of prolonged star formation activity.

Table 1
Coefficients for Equations (1) and (2)

j	a_j	b_j
0	8.144	−2.595
1	−17.620	22.021
2	16.120	−48.826
3	−5.005	51.418
4	0.6908	−23.420
5	−0.03218	3.904

Incompleteness and photometric errors. To test real conditions, the synthetic SSPs have been degraded assuming reddening and distance of the SMC, $E(B - V) = 0.08$ and $(m - M)_0 = 18.9$, and photometric errors and incompleteness as derived by Sabbi et al. (2007) from *Hubble Space Telescope* (*HST*) images of NGC 346. Figure 2(a) shows the degraded LF for populations of 5, 30, 40, 50 Myr: at the distance of SMC the excellent quality of the *HST*/Advanced Camera for Surveys (ACS) photometry guarantees perfect detectability of the peak/dip feature up to about 50 Myr. Beyond this age, the TOn becomes too faint to be detected.

Poisson fluctuations. In order to check how many stars are necessary to safely identify the TOn, we progressively reduced the number of synthetic stars belonging to the 5 Myr population, until the TOn peak was hidden by the Poisson fluctuations. This experiment indicates that about 50 stars brighter than $M_V \approx 5$ (corresponding to a cluster total mass of $\approx 500\, M_\odot$) are sufficient to identify the TOn with a significance of 2σ.

IMF, binaries, star formation duration. In Figure 2(b), the synthetic 5 Myr SSP has been modeled changing the binary fraction (50% of simulated stars have now an unresolved companion, randomly extracted from the same IMF as the primary) and the IMF exponent (1.5–3). None of these changes alters significantly the TOn position: the case with binaries is almost identical to the reference case, while the adoption of different IMFs modifies only the shape of the LF before and after the TOn peak.

In Figure 2(c) we have simulated a 10 Myr old cluster with a star formation activity that lasts 1, 3, and 5 Myr (see, e.g., Palla & Stahler 2000). As expected, with a prolonged star formation activity the LF peak grows brighter and broader. In this case, the peak magnitude provides information on the average age of the population.

Reddening. Typical of star-forming regions, the presence of highly obscuring material (foreground as well as local) can significantly dim and blur a TOn. Thus, reliable reddening estimates are fundamental to obtain unbiased ages. On the other hand, there are several regions with affordable foreground and intrinsic extinction. NGC 346 is one of them with foreground $E(B - V) \sim 0.08$ and internal $\lesssim 0.1$ mag (as deduced from the upper MS), which contributes to the final uncertainty by $\approx$1–2 Myr.

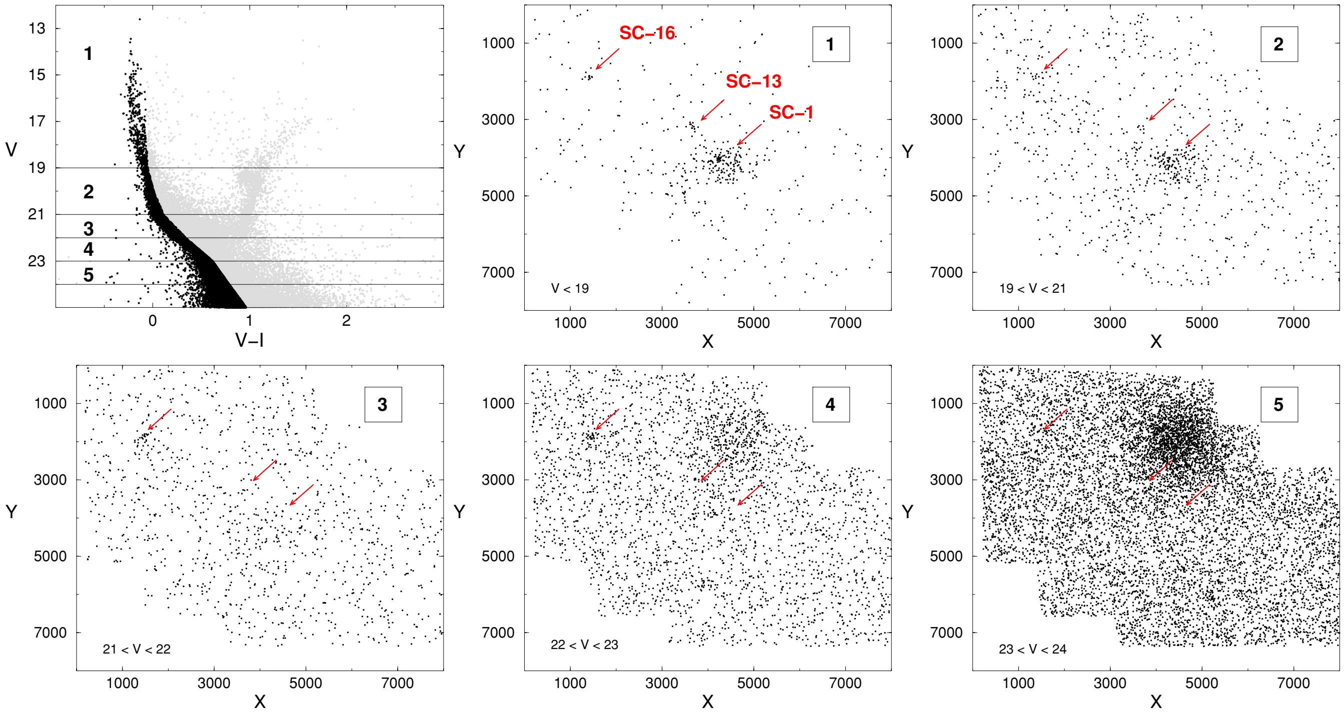

Figure 3. Top-left panel shows the CMD selection (see the text) of bona fide MS stars (black dots). Each of the other panels shows the spatial distribution of these MS stars for the labeled range of magnitudes.

3. IDENTIFICATION OF THE TOn IN EXTRAGALACTIC STAR-FORMING REGIONS: THE CASE OF NGC 346

Our goal is to study how star formation develops in extragalactic star-forming regions. In the CMD of these regions, the MS is often contaminated by young fore/background stars, and membership information is available for a safe decontamination only in a few cases. The presence of the field MS partially fills the LF dip and sensibly lowers the significance of the TOn in the LF.

To get around the problem of contamination, we propose to combine the fact that, by definition, no sub-cluster member on the MS can be fainter than the TOn, *together* with a careful analysis of the spatial distribution of the stars in the region. The procedure we suggest has three main steps. (1) Selection of bona fide MS stars (both members and non-members of the clusters) of all magnitudes. In order to take into account photometric errors and reddening, we consider all the stars bluer than a ridge line appropriately redder than the theoretical ZAMS. (2) Division of the selected MS stars into bins of progressively fainter magnitude. For each bin of a given magnitude, the spatial distribution of stars is examined to assess whether the sub-clusters are still visible. When a sub-cluster is clearly identified up to a given magnitude, but it disappears in the fainter maps, we identify the magnitude of its TOn. This is because we have reached the magnitude where the sub-cluster members have not yet reached the MS, and MS stars fainter than this limit do not belong to that sub-cluster. In order to evaluate the statistical significance of the sub-cluster disappearance from the maps, for each of the three sub-clusters we built a stellar density radial profile and we evaluated the contribution from different magnitude bins. For field stars, we expect a flat stellar density profile, while a decrease in stellar density is the typical signature of a sub-cluster. The range of magnitudes where the transition between the two profiles occurs identifies the apparent magnitude of the TOn. (3) Age determination of the sub-clusters. After applying reddening and distance modulus corrections, we use Equation (1) to translate the sub-cluster TOn magnitude into an age. The final uncertainty is fixed by the bin width, which is, in turn, chosen to obtain an acceptable number of counts per bin.

To test the strength of our method, we applied it to the star-forming region NGC 346 in the SMC, whose images acquired by the *HST* ACS have revealed a wealth of young sub-clusters containing several PMSs (Sabbi et al. 2007). This region provides excellent conditions in which to test our method because its recent strong activity supplies an outstanding sample of PMS stars (Nota et al. 2006). The complexity of its structure, with several non-coeval sub-clusters, requires a method able to trace the temporal sequence of events leading to the present configuration. In this Letter, we focus on three of the richest sub-clusters, SC-1, SC-13, and SC-16, as defined by Sabbi et al. (2007). Their location in the region can be seen in their Figure 8.

Figure 3 summarizes our analysis of NGC 346. To select only MS stars, we used a ridge line 0.05 mag redder than the theoretical $Z = 0.004$ ZAMS. We considered all the stars bluer than this line as bona fide MS stars and divided them into six bins of different sizes. Bona fide MS stars are drawn in black in the top-left panel of Figure 3, where all the other stars are marked in gray. The other five panels show the spatial distribution of the bona fide MS stars for progressively fainter bins of magnitude. Analyzing these maps, we find that the central sub-cluster SC-1 is well visible down to $V = 21$, while no obvious spatial structure resembling SC-1 is observable in the fainter maps. The sub-cluster SC-16, on the contrary, is still clearly visible down to $V = 23$. Beyond this limit, also SC-16 vanishes. The small sub-cluster SC-13 is recognizable at least to $V = 21$. Note that the stellar agglomeration appearing at $V = 22$ corresponds to the 4–5 Gyr turnoff stars of the older cluster BS90 (see, e.g., Sabbi et al. 2007) in the foreground of NGC 346.

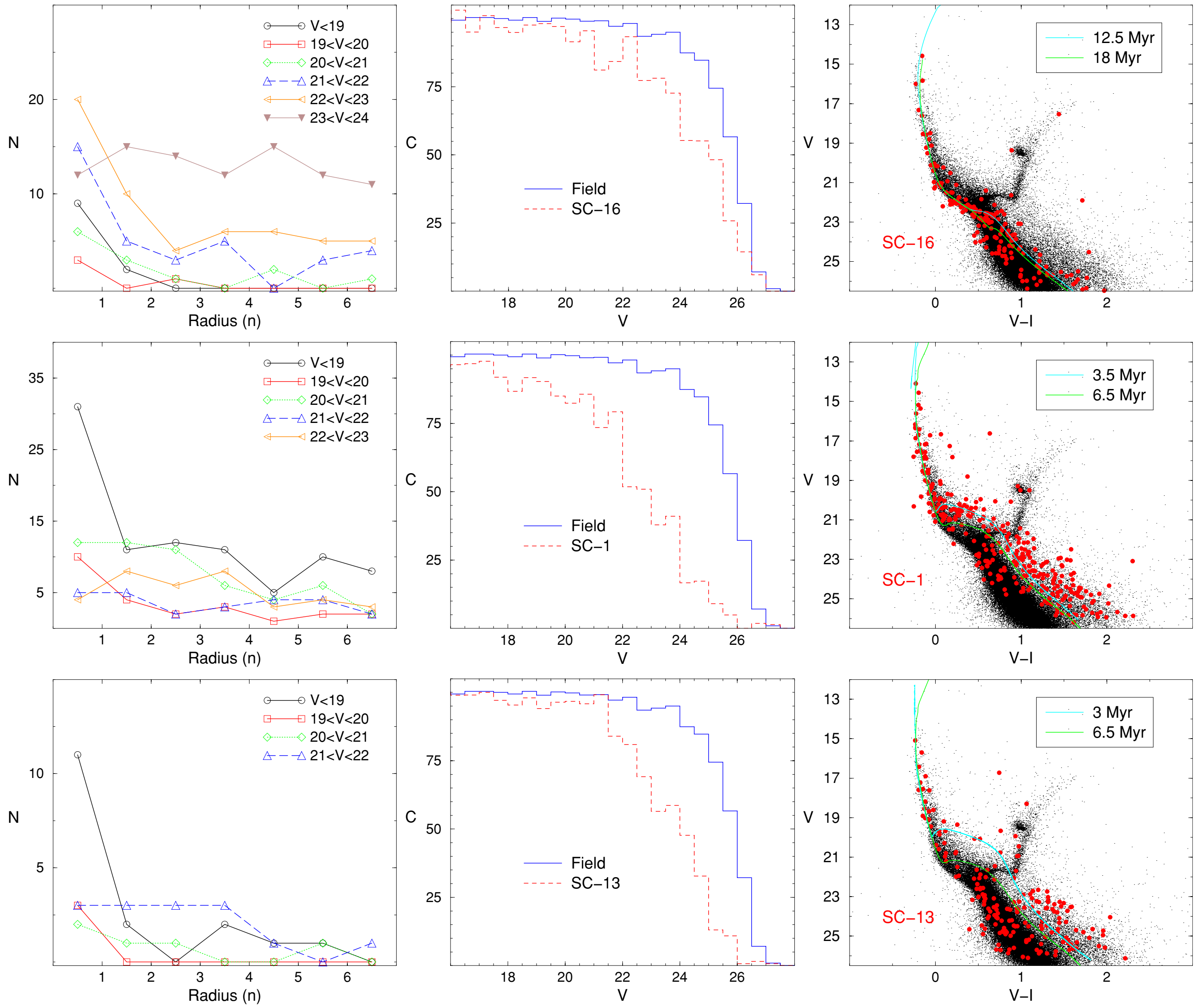

Figure 4. Left-hand panels: radial distribution of MS stars near the centers of SC-16 (top), SC-1 (middle), and SC-13 (bottom). Different curves correspond to the indicated ranges of magnitude. The abscissa is in units of n, where n is related to the distance d from the sub-cluster center by $d = \sqrt{n} \times 150$ pixels. Middle panels: completeness for the labeled sub-clusters (dashed line) and field stars (solid line). Right-hand panels: CMDs for all stars within 150 pixels from the center of SC-1 (top panel), SC-16 (middle panel), and SC-13 (bottom panel). Red dots indicate sub-cluster stars while black dots stand for the entire data sample. Isochrones of the indicated ages are also shown.

In order to test the significance of the sub-clusters, we examined the radial density profile of the three sub-clusters as a function of magnitude (Figure 4, left panels). The profiles are calculated using annuli of equal area centered on the highest density peak. The inner radius is fixed at 150 pixels. To exclude any completeness issue in these crowded regions, we also show in the middle panels of Figure 4 the completeness factors obtained from the extensive artificial star tests performed by Sabbi et al. (2007), for all stars within 100 pixels from the centers of SC-16, SC-1, and SC-13. To further test the final ages, theoretical isochrones are over-imposed on the CMDs (right panels of Figure 4).

3.1. SC-16

The first row in Figure 4 shows the MS radial profiles (left panel), the completeness curves (middle panel), and the CMD (right panel) for SC-16. The compact morphology of this sub-cluster is evident: the radial profile of MS stars brighter than $V = 23$ rapidly drops with distance from the center, while the distribution of less luminous MS stars is constant. This confirms that the TOn magnitude is between 22 and 23, thereby constraining the first generation of stars to have formed between 12.5 and 18 Myr ago. The upper right panel of Figure 4 shows the corresponding isochrones superimposed to the SC-16 CMD (all stars within 150 pixel from the center): it is reassuring to see that below the 18 Myr TOn, the sub-cluster stars move away from the MS, confirming that the MS deficit in the map is a genuine evolutionary effect. Concerning the completeness, although the sub-cluster region loses stars faster than the field, for magnitudes $V < 23$ this effect is not severe (compared to the field, less than 25% of stars are lost). By comparing our age estimate to independent determinations we find good agreement with both Sabbi et al. (2007) (15 ± 2.5 Myr) and Hennekemper et al. (2008) (5–15 Myr).

3.2. SC-1

The case of SC-1 (second row in Figure 4) is quite different. Here, the extended spatial morphology produces a gradual decrease in the MS radial profile rather than an abrupt drop at $V \approx 21$. Radial profiles for fainter magnitudes are quite flat. Assuming a conservative bin uncertainty of 1.5 mag on the TOn magnitude, the star formation onset is expected between 3.5 and 6.5 Myr ago, in agreement with the estimate by Sabbi et al. (2007) (3 ± 1 Myr). Both the 3.5 and the 6.5 isochrones are overlaid on the SC-1 CMD. As suggested by radial profiles at $V = 21$, there is a clear signature of a PMS TOn, with a large sample of stars still in the PMS phase. Our 6.5 Myr isochrone fits the upper MS morphology, including the TOn, very well and fits the PMS blue envelope as well. The few MS stars below the TOn are likely contamination of the SMC field and/or stars of the old cluster BS90 (the presence of three clump stars endorses this hypothesis). The absence of any star on the MS around $V \sim 21.5$ and the morphology of the CMD for the vast majority of the stars, which seems to follow the isochrone with PMS included, further support our conclusion. The measured completeness (middle panel) is better than 75% and cannot account for such a reduction.

3.3. *SC-13*

The third row of Figure 4 shows the sub-cluster SC-13. As for SC-1, the MS density profiles of SC-13 are declining down to $V > 21$. However, due to the poor statistics, we can only state that the cluster formation started sometime in the last 6 Myr. There is a further clue suggesting that SC-13 is actually younger than 6 Myr: a close inspection of the CMD (right panel) reveals that most of the probable intermediate-mass PMS stars are aligned with the 3 Myr isochrone. In agreement with this finding, most of the low-mass PMS stars are redder than the 3 Myr isochrone. This age is also found by Sabbi et al. (2007) (3 ± 1 Myr) and Hennekemper et al. (2008) (0.5–2.5 Myr).

4. DISCUSSION AND CONCLUSIONS

The evolution of young star-forming regions in their earliest stages is still quite unknown. For very young clusters, with ages of tenths to a few Myr, the identification of the turnoff is usually hampered by the paucity of massive stars. However, when a cluster is sufficiently young to harbor PMS stars, the luminosity of its TOn provides a robust indication of its age. Furthermore, while the PMS evolutionary models still suffer several limitations, the simple comparison of TOn luminosities is a reliable measure of relative ages.

In the LF, the TOn is a narrow peak followed by a dip. The TOn is very sensitive to age: for a ∼30 Myr old stellar population the luminosity of the TOn changes by ∼0.08 mag Myr^{-1}, but at ∼20 Myr it already changes by ∼0.15 mag Myr^{-1}, and by ∼0.33 mag Myr^{-1} at 3 Myr.

To guarantee a safe TOn identification, it is important to select targets with low or well-known reddening. In the visual, this currently excludes Galactic clusters like Westerlund 1–2, NGC 3603, Arches and Quintuplet, but good targets can be found in the solar vicinity and in some nearby irregular galaxies like the Magellanic Clouds and IC1613.

In this Letter, we have presented a new method for investigating how star formation develops in complex extragalactic young clusters such as NGC 346 in the SMC.

Our method combines the analysis of the star clusters' stellar densities profiles with the notion that in a cluster no star on the MS can be fainter than the cluster TOn. This approach has the advantage of strongly reducing the uncertainties introduced by the contamination to the CMD by young stars that do not belong to the cluster, ultimately affecting the TOn detectability in both CMD and LF.

Clearly, there are limitations to the applicability of the method. The bona fide MS selection may include intruders like PMS and stars evolved off the MS, reducing the TOn visibility. The issue is particularly thorny at ages larger than about 30 Myr, because the PMS isochrones are close to the ZAMS (see Figure 1(a)). The method relies on the assumption that the formation sites are agglomerations of stars: if for some reason the newborn stars formed in isolation or, drifting apart, were too diluted to be detected as aggregates, the method would not be applicable. In this respect, the study by Pfalzner (2009), exploiting the density–radius relation to date nearby clusters younger than 20 Myr is interesting and reassuring.

We applied the TOn method to NGC 346 in SMC, and we found that the onset of the star formation in the sub-cluster SC-1 was between 3.5 and 6.5 Myr, in the sub-cluster SC-13 3 Myr ago or less and in SC-16 between 12.5 and 18 Myr ago, in good agreement with the results from the literature.

Having established the effectiveness of our method, the next steps will be to (1) incorporate near-infrared photometry and use it to study extinguished regions, where measurements of the upper MS are difficult to carry out and (2) undertake comparative studies of the duration and spatial patterns of star formation in Magellanic Cloud regions ranging from the giant 30 Dor complex to the comparatively isolated NGC 602 cluster.

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