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Pre-main-sequence stars older than 8 Myr in the Eagle nebula

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ABSTRACT

Attention is given to a population of 110 stars in the NGC 6611 cluster of the Eagle nebula that have prominent near-infrared excess and optical colours typical of pre-main-sequence (PMS) stars older than 8 Myr. At least half of those for which spectroscopy exists have a Hα emission line profile revealing active accretion. In principle, the $V - I$ colours of all these stars would be consistent with those of young PMS objects (<1 Myr) whose radiation is heavily obscured by a circumstellar disc seen at high inclination and in small part scattered towards the observer by the back side of the disc. However, using theoretical models it is shown here that objects of this type can only account for a few per cent of this population. In fact, the spatial distribution of these objects, their X-ray luminosities, their optical brightness, their positions in the colour–magnitude diagram and the weak Li absorption lines of the stars studied spectroscopically suggest that most of them are at least eight times older than the ∼1 Myr-old PMS stars already known in this cluster and could be as old as ∼30 Myr. This is the largest homogeneous sample to date of Galactic PMS stars considerably older than 8 Myr that are still actively accreting from a circumstellar disc and it allows us to set a lower limit of 7 per cent to the disc frequency at ∼16 Myr in NGC 6611. These values imply a characteristic exponential lifetime of ∼6 Myr for disc dissipation.

Key words: accretion, accretion discs – scattering – protoplanetary discs – circumstellar matter – Hertzsprung–Russell and colour–magnitude diagrams – stars: pre-main-sequence.

1 INTRODUCTION

In the current paradigm of star formation (see e.g. Lada 1999, and references therein) conservation of angular momentum during the collapse of cloud cores leads to the formation of circumstellar discs around newly born stars. The presence and evolution of circumstellar discs is important both for planets, which find in discs the natural sites for their formation, and for the star itself, whose mass growth during the pre-main-sequence (PMS) phase depends on accretion of gas from the disc. Therefore, the time-scale of disc dissipation sets crucial constraints for models of stars and planets formation.

Over the past decade, many studies have tried to address these issues observationally. Based on the assumption that a near-infrared (NIR) or mid-infrared (MIR) spectral excess in young stars is the unambiguous signature of an inner circumstellar dusty disc, as originally suggested by Lada & Wilking (1984), these works have looked at the fraction of objects in stellar systems of various ages that still show NIR and MIR excess in their spectra (e.g. Haisch, Lada & Lada 2001; Bouwman et al. 2006; Sicilia-Aguilar et al. 2006; Hernández et al. 2008). This analysis suggests a rapid decline of the disc frequency as age proceeds, with 50 per cent of low-mass stars losing their inner dust discs within ∼3 Myr. However, disc evolution is poorly constrained for ages above ∼5 Myr, due to small number statistics both in the number of star-forming regions and in the total number of stars studied. A few well-established cases of long-lived dusty discs have been found so far. These include the double cluster h and χ Persei, with up to 8 per cent of its members still showing infrared (IR) excess at 8 μm at an age of ∼13 Myr (Currie et al. 2007a), and the Scorpius–Centaurus (Sco–Cen) OB association, with about one third of the stars showing IR excess at 24 μm at ages in the range ∼10–17 Myr (Chen et al. 2011).

Additional uncertainties on the actual disc fraction are introduced by the effect of nearby massive stars, which are known to cause the photoevaporation of the circumstellar discs on a more rapid time-scale (e.g. Störzer & Hollenbach 1999; De Marchi, Panagia &

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Romaniello 2010a; Guarcello et al. 2010b; Mann & Williams 2010). Furthermore, the observations cited in the previous paragraph do not probe the gas in the discs (except for the case of h and χ Persei; see Currie et al. 2007b), which is expected to account for ~99 per cent of the disc mass. Therefore, most of those measurements cannot provide strong direct constraints on the late phases of star formation or on mass accretion.

Fedele et al. (2010) have compared the fraction of actively accreting stars with spectral type later than K0 in seven nearby clusters and associations with that of stars surrounded by dusty discs in the same systems. They found that at any given age the fraction of stars with ongoing mass accretion (as determined from the properties of the Hα emission line) is systematically lower than that of stars with NIR or MIR excess, and concluded that the exponential decay time-scale for mass accretion (2.3 Myr) is even shorter than the time-scale for the dissipation of dusty discs mentioned above (3 Myr). We note, however, that this analysis does not explicitly take into account the effects of temporal variability of the Hα emission line (see e.g. Johns & Basri 1995; Alencar & Batalha 2002; Jayawardhana et al. 2006). Therefore, it only sets a lower limit to the fraction of actively accreting stars, but the time-scale for the dissipation of gaseous discs is likely longer than 2.3 Myr (see also Bell et al. 2013).

Longer lived gaseous discs are known to exist in well-studied older Galactic objects such as h and χ Persei (Currie et al. 2007b), MP Muscae (Argiroffi, Maggio & Peres 2007), 49 Ceti (Hughes et al. 2008) and HD 21997 (Moór et al. 2011) and appear to be needed to explain the large number of actively accreting PMS stars with ages well above 10 Myr recently discovered in the Magellanic Clouds. Studies of the regions around SN 1987A and 30 Dor in the Large Magellanic Cloud (LMC) have revealed populations of PMS objects with considerable Hα excess emission (i.e. an Hα equivalent width above 20 Å), showing ages of ~15–20 Myr and a spatial distribution markedly different from that of younger ($\lesssim$5 Myr) PMS stars (De Marchi et al. 2010a; De Marchi et al. 2011a; Spezzi et al. 2012). Similarly, NGC 346 and NC 602 in the Small Magellanic Cloud contain a conspicuous population of ~20 Myr old PMS objects with mass accretion rates higher than 10^{-8} M$_\odot$ yr^{-1} (De Marchi et al. 2011b,c, 2013).

The low metallicity of the Magellanic Clouds could be at the origin of the elevated mass accretion rates and older PMS ages measured in these works, as suggested by De Marchi et al. (2010, 2011c) and Spezzi et al. (2012). However, also in the Milky Way there are examples of active PMS stars with solar metallicity that are older than ~10 Myr. They were detected through their excess Hα emission e.g. in NGC 3603 (Beccari et al. 2010; Correnti et al. 2012) and in NGC 6167 (Baume et al. 2011). These relatively massive clusters host also stars of spectral type B or earlier, revealing an environment of intense star formation, more similar to that of the Magellanic Clouds clusters mentioned above than to the very nearby regions of diffuse star formation studied e.g. by Haisch et al. (2001) and Fedele et al. (2010). Therefore, it is fair to wonder whether the paucity of PMS stars with dusty discs or active mass accretion for ages older than ~5 Myr measured by these authors could be affected by small number statistics, by uncertainties in the membership selection and perhaps more importantly by different environmental conditions.

A very interesting object in this respect is NGC 6611, at the centre of the Eagle nebula (M 16) some 1750 pc away, whose stellar populations have been recently the subject of a ground- and space-based multiwavelength study presented in a series of papers by Guarcello et al. (2007, 2009, 2010b). Using a number of reddening-free colour indices based on panchromatic observations at visible and IR wavelengths, these authors have searched for and identified stars with IR excess and have derived their physical parameters. In light of the appreciable IR excess, these objects have been classified as candidate disc-bearing PMS stars. Yet a conspicuous number of them appear relatively blue in optical colours and, in the (V, $V-I$) colour–magnitude diagram (CMD), they are consistent with PMS evolutionary ages in excess of ~10 Myr. Recently, medium resolution spectroscopic observations ($R \simeq 17\,000$) have been carried out for 20 of these objects by Bonito et al. (2013). Analysis of the Hα line profiles and of their temporal variations show that 10 of these stars (50 per cent) are confirmed members and an additional six (30 per cent) are likely members, with typical line widths of ~200 km s^{-1}. This shows that accretion/outflow processes are at work and that these objects must be still relatively young. The question to answer is how young.

In this work, we show that their spatial distribution, their X-ray luminosities, their optical brightness and their positions in the CMD indicate that most of these stars are at least eight times older than the ~1 Myr-old PMS population already known in this cluster. The structure of the paper is as follows: the data at the basis of the photometric catalogue are discussed in Section 2; the stars with peculiar blue optical colours are described in Section 3, where we also set constraints on the correction for interstellar reddening. Sections 4 and 5 present their radial distribution and X-ray luminosities, whereas Section 6 addresses the effects that a circumstellar disc could have on their optical colours. Section 7 is dedicated to the discussion of these results, while a summary and conclusions follow in Section 8.

2 DATA SAMPLE

The data analysed in this work were extracted from the multiband photometric catalogue of NGC 6611 and of the surrounding M 16 cloud compiled by Guarcello et al. (2010b). The catalogue contains in excess of 190 000 sources, in a region of 33 arcmin × 34 arcmin around the centre of NGC 6611. Each object is detected in one or more of the following bands: optical observations in B, V and I from the ground (28 827 sources detected; see Guarcello et al. 2007); NIR observations in J, H and K from the Two Micron All Sky Survey (16 390 sources detected; see Guarcello et al. 2007) and from the United Kingdom Infrared Deep Sky Survey (159 999 sources detected; see Guarcello et al. 2010b); observations with the *Spitzer Space Telescope* Infrared Array Camera (IRAC) in four bands centred at 3.6, 4.5, 5.8 and 8.0 μm (41 985 sources detected; see Guarcello et al. 2009); and X-ray observations with the *Chandra X-ray Observatory* ACIS–I camera (1755 sources detected; see Guarcello et al. 2010b).

In order to select from the catalogue only candidate cluster members with circumstellar discs, Guarcello et al. (2010b) have looked for objects with NIR excess emission, using the standard [3.6] − [4.5] versus [5.8] − [8.0] colour–colour diagram defined by the *Spitzer*/IRAC bands (e.g. Allen et al. 2004), as well as several reddening-free colour indices involving a combination of visible and NIR bands (for details on the indices see Guarcello et al. 2007 and Damiani et al. 2006). Note that, even though Guarcello et al. (2007, 2009, 2010b) identified stars with excess in the *JHK* bands using the reddening-free colour indices, these objects do show excess even in the more canonical colour–colour diagrams involving just the NIR bands. As extensively discussed in those papers (and particularly in Guarcello et al. 2009), the use of reddening-free Q indices provides a very efficient diagnostic for the

Table 1. Photometric catalogue, listing the ID number, equatorial coordinates (J2000), V and I magnitudes with their uncertainties and whether the objects was detected in the X rays (Y = yes, N = no, while O indicates that the object is outside the field covered by the X-ray observations). The complete table is only available online.

ID	RA	Dec.	V	δV	I	δI	X
1	274.8771	−13.7581	20.95	0.08	16.89	0.01	O
2	274.8531	−13.6117	13.95	0.01	12.64	0.01	O
3	274.7775	−13.7602	16.85	0.01	14.37	0.02	Y
4	274.7183	−13.7356	21.57	0.05	17.09	0.02	Y
5	274.4489	−13.6591	14.68	0.01	13.01	0.01	N

identification of Class II sources, particularly of those with moderate disc inclination to the line of sight, thanks to the inclusion of the optical and J bands. Conversely, traditional colour–colour diagrams in the IRAC bands are better suited for the identification of very young embedded stellar objects or of Class II stars with highly inclined discs.

Guarcello et al. (2010b) identified in this way 834 objects in NGC 6611, which are classified as bona fide cluster members with circumstellar discs. A total of 624 of them are detected in the V and I bands, with V magnitude uncertainties smaller than 0.1 mag and $V-I$ colour uncertainties not exceeding 0.15 mag. These are the objects whose properties we study in this work. Their coordinates and photometry are collected in Table 1, which is only available online and is directly extracted from the catalogue of Guarcello et al. (2010b).

3 BLUE STARS WITH EXCESS

The CMD corresponding to the objects in Table 1 is shown in Fig. 1, where apparent magnitudes before any correction for extinction are shown. The 624 disc-bearing candidates are indicated with large dots, whereas with small grey dots we show, for reference, all other stars detected in V and I in this field, with the same constraints on photometric uncertainty as for cluster members. Guarcello et al. (2010a) have shown that all these objects are bona fide cluster members. However, while most have colours and magnitudes typical of young (∼1 Myr old) PMS stars, about 20 per cent of them appear to have a $V-I$ colour too blue for their V magnitude and/or to be too faint in V for their $V-I$ colours for such a young age.

This discrepancy becomes clear when one compares the observed CMD with theoretical PMS isochrones. The solid lines in Fig. 1 represent the PMS isochrones of Siess et al. (2000) for stars with solar metallicity and ages of 0.1, 0.25, 0.5, 1, 2, 4, 8, 16, 32 and 64 Myr (from right to left). All isochrones are reddened adopting the average value of the extinction derived by Guarcello et al. (2007) for the stars in NGC 6611, namely $A_V = 2.6$, and assuming a distance modulus $(m-M)_0 = 11.2$. The thick dashed line corresponds to the zero-age main sequence (ZAMS), from the models of Marigo et al. (2008) for solar metallicity and the same extinction values, and it agrees well with the 64 Myr PMS isochrone. The dot–dashed line shows the same ZAMS for $A_V = 0$.

The peculiarity in this diagram, as noted by Guarcello et al. (2010a), is the conspicuous group of objects with $16 < V < 19$ and with $1.2 < V-I < 1.8$. All these stars have NIR excess, as explained above, and as such are candidate disc bearing objects, but in the CMD they appear rather blue, i.e. near or at the ZAMS. Hereafter, we will call these objects ‘blue stars with excess’ or BWE, following Guarcello et al.’s nomenclature. For simplicity, all other candidate disc-bearing objects in the field will be called

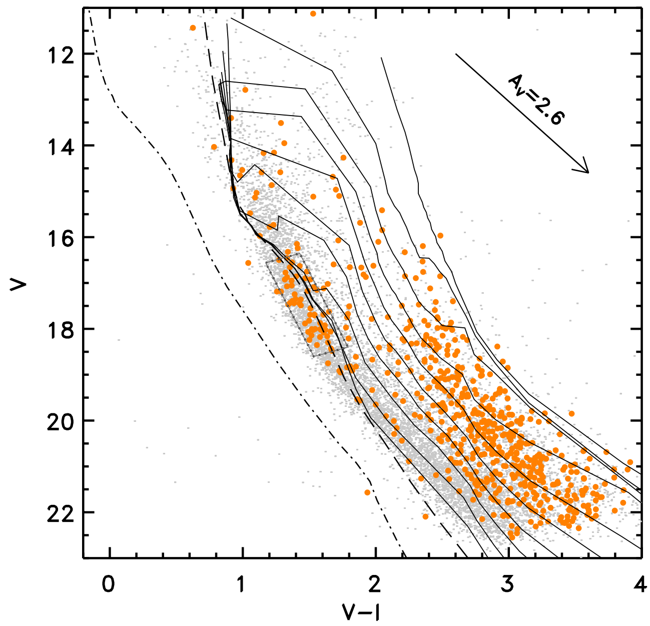

Figure 1. CMD of the stars in the field, before reddening correction. The dots correspond to the 624 disc-bearing stars with small photometric uncertainties, i.e. less than 0.1 mag in V and 0.15 mag in $V-I$. Small grey dots show all other stars observed in this field, with the same selection on photometric uncertainty. The thin solid lines are the PMS isochrones of Siess, Dufour & Forestini (2000) for stars of solar metallicity and ages of 0.1, 0.25, 0.5, 1, 2, 4, 8, 16, 32 and 64 Myr, from right to left, for a distance modulus $(m-M)_0 = 11.2$ and average reddening $A_V = 2.6$ (the corresponding reddening vector is shown by the arrow). The dashed line shows the ZAMS of Marigo et al. (2008) for stars of solar metallicity and for $A_V = 2.6$, while, for reference, the dot–dashed line shows the same ZAMS for $A_V = 0$.

‘red stars with excess’ or RWE. Although a mismatch between the optical and IR catalogues could cause a spurious NIR excess in otherwise normal main-sequence (MS) stars, Guarcello et al. (2010b) have shown that the probability of mismatches is very low. Furthermore, as mentioned in Section 1, Bonito et al. (2013) have shown that the Hα emission line profile of at least half of the BWE stars studied spectroscopically reveals ongoing accretion. Finally, as we will show in Section 4, most BWE stars are located outside of the cluster centre whereas mismatches would be more likely in the central regions, where the density of optical sources is higher.

For the same reason, also a binary origin can be excluded for BWE stars, since binaries are most likely to be found in the central regions of clusters (e.g. Sollima et al. 2010). Furthermore, in the photometry unresolved binaries would appear systematically brighter and redder than individual components, so we can exclude that BWE objects are binary RWE stars.

Instead, the positions of the BWE stars in the CMD suggest an older age than that of the more numerous RWE stars clustered around $V \simeq 20$, $V-I \simeq 3$ with isochronal ages of order ∼1 Myr and in any case less than ∼5 Myr. The latter correspond to a population of young PMS stars already known to be present in this field (e.g. Hillenbrand et al. 1993), while a direct comparison with the PMS isochrones in Fig. 1 would suggest typical ages in excess of ∼8 Myr for BWE objects. In principle, younger ages for the BWE stars would still be possible if these objects had a lower metallicity than that of RWE stars. However, comparison of their colours with the Pisa PMS evolutionary tracks for a wide range of metallicities (Degl’Innocenti et al. 2008; Tognelli, Prada Moroni & Degl’Innocenti 2011) reveals that in order for the BWE stars to have the same age as the RWE stars they would have to be ∼20 times less metal rich, i.e. they should have $Z = 0.001$. Star-forming regions with such a low metal content are not known in the Milky Way, nor are such large metallicity differences observed in any star-forming region. Therefore, we will continue to assume that BWE stars have the same metallicity as the RWE objects, and as such their colours indicate an older age.

Even ignoring absolute ages, which may be affected by systematic uncertainties in the isochrones, Fig. 1 clearly shows that if the BWE objects are at the distance of NGC 6611 and are affected by a similar extinction, they must be considerably older than RWE stars, by more than an order of magnitude. For instance, using semi-empirical model isochrones Bell et al. (2013) recently concluded that the most probable age for young PMS stars in NGC 6611 is ∼2 Myr, rather than 1 Myr as found by Guarcello et al. (2007), but this would not change the relative age difference between RWE and BWE stars. In fact, if PMS ages are systematically underestimated, as Bell et al. (2013) suggest, the age difference between RWE and BWE stars would grow even larger.

On the other hand, if patchy interstellar extinction is present inside NGC 6611, it is possible that the BWE objects are less reddened than the other stars and appear older in Fig. 1 just because one and the same reddening value ($A_V = 2.6$) is applied to all isochrones. Similarly, if the BWE stars are not at the distance of the Eagle nebula but somewhere else along the line of sight, they might be bona fide young PMS stars. Therefore, it is necessary to understand the presence and properties of interstellar extinction towards these objects and where they are located with respect to NGC 6611, as well as the effects of field contamination, before we can assign a relative age to them.

3.1 Extinction towards the BWE stars

In their study of NGC 6611, Hillenbrand et al. (1993) investigated previous suggestions (Hiltner & Morgan 1969; Kamp 1974; Neckel & Chini 1981; Chini & Krügel 1983; Chini & Wargau 1990) that the reddening law towards NGC 6611 is different from that of the average interstellar medium. They concluded that, inside the cluster, the total-to-selective extinction $R_V = A_V/E(B-V)$ is 3.75 and as such it is higher than the canonical interstellar value of 3.1 (e.g. Mathis 1990). However, they did not find any systematic variation in the value of R_V or $E(B-V)$ with position in the cluster, contrary to the suggestions made by Walker (1961) and Sagar & Joshi (1979) that reddening in NGC 6611 increases proceeding westwards and northwards.

Guarcello et al. (2007) repeated the analysis carried out by Hillenbrand et al. (1993) using improved photometry and considering separately stars with and without X-ray emission. They found a somewhat unusual extinction law, but did not confirm the high R_V value found by Hillenbrand et al. (1993), concluding instead that $R_V \simeq 3.3$ is applicable to all objects in the field. In a subsequent paper, Guarcello et al. (2010b) also derived an extinction map of the region using bona fide cluster members. These authors conclude that the reddening is rather uniform in the central ∼10 arcmin radius of NGC 6611, confirming the average value of $A_V = 2.6$ derived before. However, they also noticed a considerable increase in the reddening north and northeast of the cluster centre, with local A_V values reaching as high as 18 mag in regions coinciding with known prominent nebular structures.

As we will show in Section 4, the BWE objects are distributed rather uniformly over these fields and, as such, only very few of them occupy the regions with very high extinction to the north

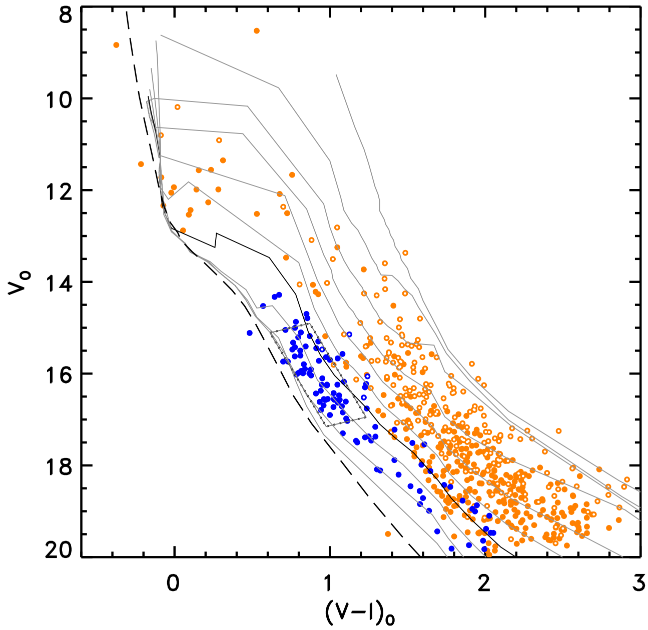

Figure 2. Dereddened CMD of all stars with discs. The light grey dots (orange in the online article) are RWE objects, to which we have applied a reddening correction of $A_V = 2.6$. The dark dots (blue in the online article) are BWE stars, to which we have assigned $A_V = 1.45$. The solid lines correspond to the same isochrones as shown in Fig. 1, for a distance modulus of $(m-M)_0 = 11.2$, with the 8 Myr isochrone shown as a thicker line. The same distance modulus has been applied to the ZAMS of Marigo et al. (2008), shown here as a dashed line. The stars shown as the empty circles are those detected in the X-rays. The meaning of the dotted box around BWE stars is discussed in Section 7.

and northeast of the centre. In fact, if they are in the foreground, they might be affected by lower extinction, as mentioned above. Actually, Guarcello et al. (2007) already concluded that stars in the foreground of NGC 6611 are subject to a lower extinction value, namely $A_V < 1.45$, and the fact that many BWE stars at $V \simeq 17$ appear bluer than the reddened ZAMS supports this hypothesis.

In Fig. 2, we show a dereddened CMD obtained by applying a lower reddening correction to BWE objects. For practicality, the acronym BWE will be reserved for stars with NIR excess (large dots) that in Fig. 1 are bluer than the 8 Myr isochrone and with $V-I < 2.6$, whereas all other stars with NIR excess (i.e. candidate disc-bearing objects) will be labelled RWE. There are in total 513 RWE and 110 BWE objects.[1] In Fig. 2, we have applied to all RWE objects a reddening correction corresponding to $A_V = 2.6$ and they appear as light grey dots (orange in the online article), whereas the BWE stars are corrected for $A_V = 1.45$, which as mentioned above is the value measured for foreground field stars, and appear as dark dots (blue in the online article). If the BWE stars are associated with the cluster, their reddening will be larger than 1.45, so the adopted $A_V = 1.45$ value should be regarded as a conservative lower limit.

Even with this conservative assumption on the reddening of the BWE objects, less than 1/4 of them or 26 out of 110 would appear younger than the 8 Myr isochrone (thick line). Most of these 26 stars would still fall in the age range between 4 and 8 Myr. This means that the objects would appear a factor of ∼2 younger than

[1] In the total count of BWE objects, we also include 29 stars that Guarcello et al. (2010a) had omitted as potential foreground objects on the basis of their NIR colours.

if we had used $A_V = 2.6$ for all stars, which is an uncertainty still consistent with the formal photometric error of 0.15 mag on the $V - I$ colour. In any case, with isochronal ages in the range 16–32 Myr, the majority of BWE stars remain more than an order of magnitude older than the RWE objects. If A_V were to take on a more realistic value intermediate between 1.45 and 2.6, even older ages would result. Conversely, even with $A_V = 0$ only about half of them would appear younger than 8 Myr. For objects on the Galactic plane at a distance of 1.75 kpc, assuming a rough 1 mag kpc^{-1} of visual extinction, we could expect $A_V = 1.75$, which is in line with the range mentioned above. We can, therefore, conclude that if the BWE stars are at a distance comparable to that of the Eagle nebula no reasonable assumptions on the interstellar extinction can bring BWE and RWE stars to share the same region of the CMD, so they may well belong to different populations with different ages.

3.2 Distance to the BWE stars

Alternatively, if BWE objects are PMS stars with an age similar to that of the RWE objects, given their colours they must necessarily be more massive and hence located further away than NGC 6611. More generally, the fact that all BWE stars have NIR excess places rather stringent constraints on their distance from us. To better clarify this point, we list in Table 2 the distances and reddening values at which the BWE objects could be located for various choices of their ages. We have taken as a reference point in the CMD the barycentre of the 56 BWE stars included in the dotted box in Fig. 1, defined as the smallest parallelogram that contains the majority (i.e. 50 per cent + 1) of these objects. We have compared the colour and magnitude of its barycentre with the theoretical isochrones of Siess et al. (2000) for ages of 2, 4, 8, 16 and 32 Myr. Table 2 lists, for each age, the combination of distance and reddening giving the best match for the Galactic extinction law. This comparison shows the following.

(i) For ages of 8 Myr or less, no acceptable combination of distance and reddening can be found: objects of this type in the foreground of NGC 6611 should be several magnitudes brighter than the BWE that we observe, whereas if they were located behind the cluster a match could be found only for values of the reddening much lower than that towards the cluster itself. This is hard to imagine due to the considerable amount of interstellar extinction (e.g. Marshall et al. 2006) expected for objects of low Galactic latitude such as NGC 6611 ($b = 0.8$). Guarcello et al. (2007) already showed that the nebulosity associated with the Eagle nebula blocks or severely reddens the light of background field stars, which should otherwise appear in large numbers to the left of the ZAMS in Fig. 1 if they were less extincted than cluster stars. Furthermore, even allowing for a lower reddening than that towards NGC 6611, the paucity of BWE stars in Fig. 1 at magnitudes fainter than $V = 19$ could not be reproduced for a typical stellar initial mass function (IMF; e.g. De Marchi, Paresce & Portegies Zwart 2010b).

(ii) At ages of 32 Myr (and in general older than ∼20 Myr) PMS stars usually no longer show NIR excess. Assuming, nonetheless, that an age of this type were appropriate for the BWE stars, it would place these objects in front of NGC 6611 but not without inconsistencies: (a) it would typically require a reddening value higher than that for stars in the immediate foreground of the cluster (i.e. $A_V > 1.45$); (b) for distances of less than 1500 pc the foreground star-forming region hosting the BWE stars would have to be excessively well aligned along the line of sight to NGC 6611, even though the two regions are not part of the same complex, and this would look contrived.

(iii) For ages of 16 Myr, an excellent fit is found for a distance corresponding to that of NGC 6611 and the reddening value derived by Guarcello et al. (2007) for stars in the immediate foreground of the cluster (i.e. $A_V = 1.45$). For distances of less than 1 650 pc, however, the isochrones would be systematically too blue to reproduce the observed colours of stars brighter than $V = 15$, thereby implying a very unusual IMF.

Table 2. Best-fitting values of the reddening towards the BWE stars as a function of the assumed distance and age. For most distances and ages in the range explored no best fit is found, whereas for some the reddening should take on an unphysical negative value, indicated between square brackets.

d (pc)	$(m - M)_0$	A_V 2 Myr	4 Myr	8 Myr	16 Myr	32 Myr
1150	10.3	–	–	–	–	0.5
1250	10.5	–	–	–	–	1.3
1350	10.7	–	–	–	[−0.3]	1.6
1450	10.8	–	–	–	0.5	1.7
1550	11.0	–	–	–	0.9	1.8
1650	11.1	–	–	–	1.2	1.9
1750	11.2	–	[−1.5]	[−0.1]	1.5	2.0
2000	11.5	–	[−0.6]	0.9	–	2.2
2500	12.0	[−0.6]	0.7	1.6	–	–
3000	12.4	0.5	1.3	1.7	–	–
4000	13.0	1.2	1.6	2.2	–	–
5000	13.5	1.5	–	–	–	–

We conclude, therefore, that the only physically plausible explanation is that the BWE stars are at the distance of the Eagle nebula, in close proximity and most likely in the immediate foreground of the NGC 6611 cluster, and have ages between ∼10 and ∼30 Myr. As such, they may thus represent a generation different from that traced by RWE objects.

An additional indication of an older age for the BWE stars comes from their weak Li absorption lines. The exact amount of Li depletion for stars of about 1 $M_\odot$ like the BWE objects depends on a number of parameters and assumptions entering the models (e.g. Jeffries 2006; Tognelli, Degl'Innocenti & Prada Moroni 2012), such as the stellar mass, and in some cases large variations in abundance are seen even for objects of the same mass (e.g. Bonifacio et al. 2007). For PMS stars, however, a lower Li abundance clearly separates more evolved from very young objects (e.g. Sestito, Palla & Randich 2008). Of the 20 stars observed spectroscopically by Bonito et al. (2013), only five have a Li equivalent width EW(Li) > 100 mÅ, with a median value of 324 mÅ. For five additional objects veiling might be present, making the Li absorption line more difficult to detect. Nevertheless, according to the strong correlation between EW(Li) and age measured by Grankin (2013) for PMS stars in Taurus–Auriga, a value of EW(Li) $\simeq$ 100 mÅ suggests ages of order ∼20 Myr for objects of about a solar mass like those in our sample. At least half and possibly 3/4 of the BWE objects in the spectroscopic sample have weaker Li absorption lines, and must therefore be even older.

3.3 Field contamination

Some contamination by field stars is to be expected in the region of the CMD occupied by the BWE stars. Taking again the dotted parallelogram in Fig. 1 as representative of their location in the CMD, we have compared the number of BWE stars inside the parallelogram with those expected by the Besançon models of Galactic stellar population synthesis (Robin et al. 2003) in the same region of the CMD. Inside the parallelogram we find 1444 stars, of which 56 are classified as BWE objects, whereas in the same region of the CMD the Besançon models predict 367 stars due to field contamination. Thus, about one in four of the observed stars might not belong to NGC 6611. In principle, it could therefore seem reasonable to suppose that all 56 BWE objects inside the dotted parallelogram are simply field stars. However, as we have shown above, in order for stars in that region of the CMD to have NIR excess they must have ages of ∼16 Myr to within a factor of 2 and must be located at the distance of NGC 6611 or at most ∼100 pc in front of it. Over the entire field of view of these observations, the Besançon models predict no stars within 200 pc of NGC 6611 whose colours would place them inside the dotted region in Fig. 1. It appears, therefore, extremely unlikely that the BWE stars be field objects, also in light of their wide Hα emission lines, and we can conclude that even if the BWE objects are not intimately mixed with the young RWE members of NGC 6611, they are nevertheless associated with the M 16 complex (a precise determination of the actual location of these objects inside M 16 will be provided by future observations with *Gaia*; Perryman 2005). In the following sections, we investigate the physical properties of these two classes of stars in more detail, showing that they are indeed remarkably different.

4 RADIAL DISTRIBUTIONS

We first look at the spatial distribution of the two types of objects, which is shown in Fig. 3. Guarcello et al. (2010a) had already noticed that BWE objects are more frequent at larger distances from the central massive OB stars, but they did not address this issue in detail. Indeed, the spatial distribution of BWE stars (dark dots in panel a, shown in blue in the online article) is very different from that of RWE objects (light grey dots, shown in orange in the online article). While the latter are strongly concentrated towards the nominal centre of NGC 6611, marked with a circled cross, BWE stars are much more uniformly distributed across the field.

This is revealed more clearly by Fig. 3(b), which shows the actual radial density distributions of the two classes of stars. Both distributions have a higher density near the cluster centre. In particular, the positions of the two barycentres [shown by the thick square and triangle in Fig. 3(a), respectively for RWE and BWE objects] agree to within ∼15 arcmin of each other and of the cluster centre. On the other hand, in Fig. 3(a), BWE stars are clearly less concentrated and more uniformly distributed.

In order to characterize this difference in a more quantitative way, we have fitted the distributions with King profiles (King 1966), shown by the thin dashed and dotted lines. We find core radii $r_c \simeq 1$ arcmin (∼0.5 pc) and $r_c \simeq 3$ arcmin (∼1.5 pc), respectively for RWE and BWE objects. The r_c value quoted for BWE stars is actually a lower limit, since the King model underestimates the profile at large radii. The two distributions have a common centre (to within ∼15 arcmin), but different concentrations and density profiles. A Kolmogorov–Smirnov test (see Fig. 3c) shows that the cumulative radial distributions of the two populations are significantly different, with a probability of less than one part in 10^{13} that they are drawn from the same distribution.

The fact that BWE and RWE objects not only occupy different regions of the CMD (see Fig. 1) but also have a different spatial distribution suggests that they do not belong to the same population. Furthermore, from the analysis of their radial distributions, it appears that the RWE and BWE objects are compatible with having formed virtually at the same place, and possibly even with a similar initial structure. This might suggest that the BWE objects have

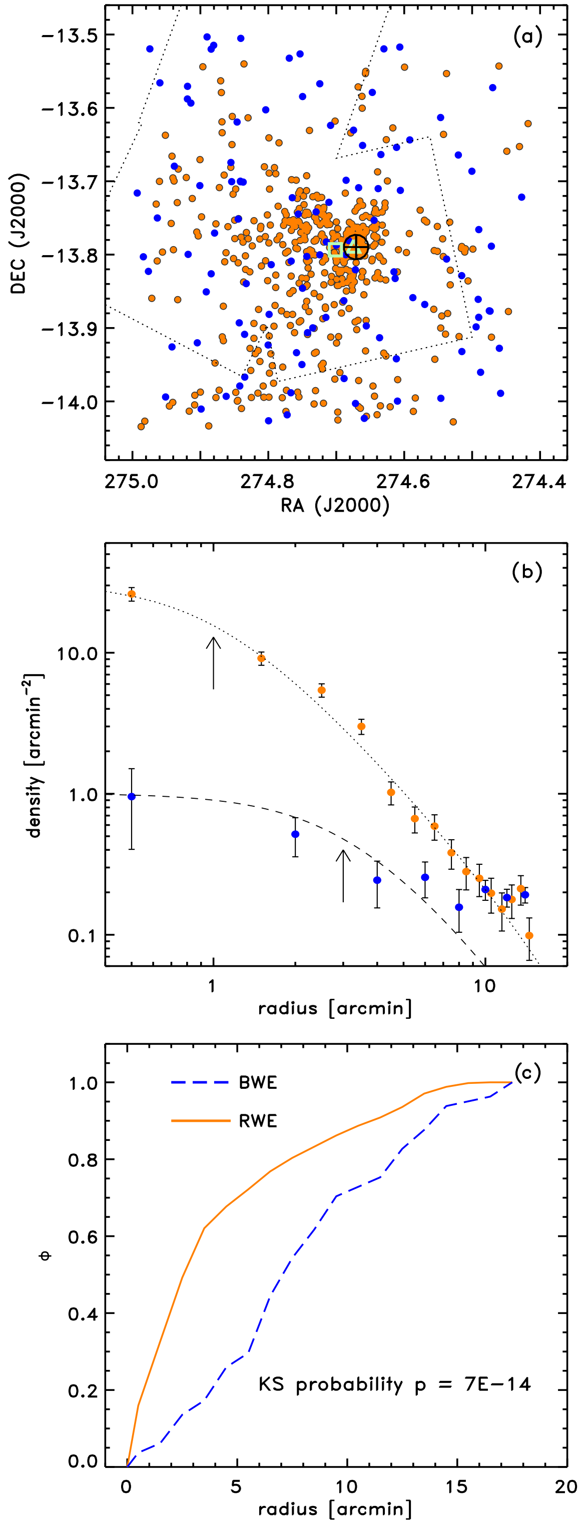

Figure 3. Panel (a): locations of BWE and RWE objects, respectively dark dots (blue in the online article) and light grey dots (orange in the online article). The nominal cluster centre is the circled cross, while the thick square and triangle mark the centre of the distributions of RWE and BWE stars, respectively. The dotted lines highlight the regions inside which X-ray observations with *Chandra* are available. Panel (b): radial density profiles of BWE (dashed line) and RWE (dotted line) objects. The dashed and dotted lines show the best-fitting King profiles with core radii of 3 and 1 arcmin, as indicated by the arrows. Panel (c): cumulative distributions of BWE (dashed line) and RWE (solid line) objects.

undergone an expansion and that they are therefore older. In this case, the distribution of BWE stars over the area covered by these observations (33 arcmin × 33 arcmin) would be consistent with an expansion velocity of ∼1 km s^{-1} (a typical value in Galactic star-forming regions) for a period of ∼15 Myr. Although this is not an independent age determination for the BWE stars, it shows that their spatial distribution is consistent with an age older than that of RWE stars. An older age for BWE stars is also supported by the X-ray properties of these objects, as we show in the following section.

5 X-RAY LUMINOSITIES

An elevated X-ray luminosity ($\log L_X \gtrsim 30$ erg s^{-1}) is a characteristic feature of young stars. Stellar X-ray emission from low-mass objects appears to reach a peak a few Myr after their birth during the early PMS phase (e.g. Preibisch & Feigelson 2005; Prisinzano et al. 2008), then decays slowly as $\sim t^{-3/4}$ until ∼1 Gyr (Preibisch & Feigelson 2005), and more rapidly thereafter (e.g. Feigelson et al. 2004).

Thus, if BWE and RWE objects have systematically different ages, their X-ray luminosities should also be different. As Table 1 shows, there is indeed a remarkable difference in the X-ray properties of the two types of objects: while only less than 6 per cent of the BWE stars (four objects in total within the dotted contour in Fig. 3a) are detected in the X rays, for the RWE objects this fraction is 46 per cent (or 203 stars). This can be seen in Fig. 2, where the objects with an X-ray detection are shown as the empty circles. That figure also shows that the four objects are systematically on the red side of the BWE distribution, suggesting that they are amongst the younger members of the BWE population. Fig. 2 would suggest an age of ∼8 Myr for two of them and less than ∼4 Myr for the two other objects, which would make them the youngest members of the BWE group.

Preibisch & Feigelson (2005) conducted an extensive study of the X-ray luminosity of PMS stars in the Orion nebula cluster (ONC). In spite of the considerable scatter of L_X (about a factor of 3) at any given age, these authors found that the median X-ray luminosity of stars in the mass range 0.5−1.2 M$_\odot$, like those considered here, drops below $\sim10^{30}$ erg s^{-1} at ages older than ∼10 Myr. The X-ray detection limit in the study by Guarcello et al. (2010b), on which Table 1 is based, corresponds to $\log L_X = 29.8$ erg s^{-1} for the assumed distance of 1.75 kpc to NGC 6611, so the paucity of X-ray sources in the BWE objects indicates that most of them are considerably older than ∼10 Myr. Note that, in principle, BWE stars could have lower accretion rates, which in turn appear to be linked to lower X-ray emission in disc-bearing stars (e.g. Flaccomio, Micela & Sciortino 2003). However, this does not imply that BWE stars are simply RWE stars at the low end of the accretion rate distribution, as the rather different spatial distribution of BWE stars would otherwise remain unexplained.

The distribution of X-ray luminosities in the ONC can be taken as a reference for NGC 6611 since the median age and overall X-ray properties of the two regions are very similar (Guarcello et al. 2012). Assuming that the relative shape of the distribution does not change over time other than for a downward shift in its peak luminosity, we conclude that a drop from 46 to 6 per cent in the number of objects above the detection limit requires a drop of a factor of ∼4 in the median X-ray luminosity. If the two BWE stars with X-ray emission younger than 4 Myr are excluded, the fraction is reduced to ∼3 per cent and the corresponding drop in luminosity grows to a factor of ∼6. These values of the drop can be converted into an age difference by direct interpolation in fig. 4 of Preibisch & Feigelson (2005) for stars of 0.5−1.2 M$_\odot$. This gives us an age definitely older than that of Chamaeleon (7 Myr) but considerably younger than that of Pleiades (80 Myr), of about 12 Myr in the first case and ∼16 Myr in the second. These are clearly approximate values, but they are in good agreement with the isochronal ages derived from Fig. 1 for the bulk of the BWE objects.

6 EFFECTS OF DISC INCLINATION

In Section 3 we showed that, regardless of the extent of the correction for interstellar extinction, the $V - I$ colours of BWE stars cannot be brought into agreement with those of RWE objects. In their study of NGC 6611, Guarcello et al. (2010a) looked at other effects that could make the young RWE stars appear bluer than their intrinsic photospheric colours. One of them is intense optical veiling caused by the accretion process, but the spectrophotometric analysis carried out by these authors allows them to exclude veiling as the cause of the very blue colours for all but a handful of the BWE stars. The recent spectroscopic study of 20 of these BWE stars conducted by Bonito et al. (2013) confirms that some veiling is possibly present only in five objects and is strong for only one of them. A more critical issue considered by Guarcello et al. (2010a) is that the presence, geometry and inclination of a circumstellar disc could appreciably alter the apparent optical colours of the stars, making them considerably bluer than their intrinsic photospheric colours. Guarcello et al. (2010a) concluded that no more than 1/3 of the BWE stars could be objects of this type. In the following, we address this effect in more detail and show that the fraction cannot be larger than a few per cent.

It is well known that, in general, reflection nebulae appear bluer than the illuminating stars because the scattering cross-section of grains is higher at shorter wavelengths (e.g. Henyey & Greenstein 1938). For the same reason, if a conspicuous fraction of the light that we receive from a PMS object is radiation scattered by the circumstellar disc, its optical colours could be bluer than those of the stellar photosphere and could make the object appear older in the CMD. This in turn requires the bulk of the optical photospheric flux to be blocked (i.e. absorbed and hence reddened) by an almost edge-on circumstellar disc, which makes at the same time the object considerably fainter. We clarify this scenario first with a simple order of magnitude calculation and then we confirm its validity using models of the spectral energy distribution of PMS stars.

6.1 Order of magnitude estimate

In the approximation of an infinite disc radius, a flat disc can intercept 1/4 of the stellar luminosity $L_\star$ (e.g. Lynden-Bell & Pringle 1974). For a flared disc this fraction can be higher, but also the effect of obscuration will increase with disc thickness, so the approximation remains valid.[2] Each face of the disc intercepts half of this radiation, or $L_\star/8$ (see Fig. 4a), but the fraction that can effectively be scattered towards an observer seeing the disc face-on is less, since the albedo of astrophysical dust in the optical is typically less than ∼0.5 (e.g. Mathis, Mezger & Panagia 1983; Natta & Panagia 1984). Thus, the fraction of scattered stellar light received by an observer seeing the face-on disc never exceeds $L_\star/16$, i.e. 3 mag fainter than the star itself. Therefore, as long as the disc does not

[2] An opaque disc is assumed, since for an optically thin disc these effects are much less important.

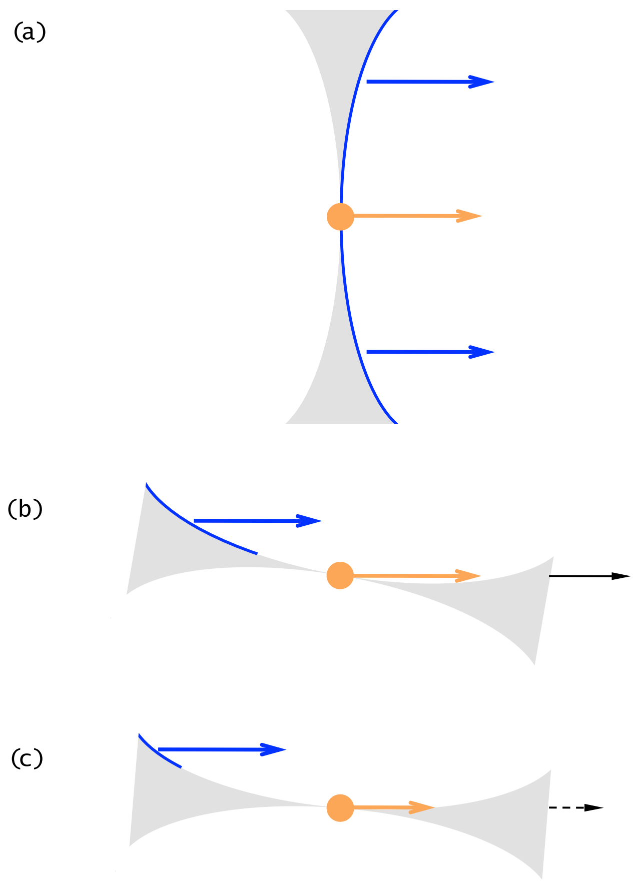

Figure 4. Panel (a): if the disc is seen face-on, the observer (on the right) can only see the light scattered by one side of the disc (thick line, shown in blue in the online article). Panel (b): at higher inclination, a point is reached when the light scattered by the near side of the disc no longer reaches the observer. Panel (c): when the inclination increases further, the light of the star will be absorbed (and reddened) by the near side of the disc and only a portion of the far side of the disc can effectively scatter light towards the observer.

block the direct view to the star, the preferential scattering of blue light cannot significantly alter the $V - I$ colour of the object.

As the inclination of the disc increases, a point is reached when the light scattered by the near side of the disc no longer reaches the observer, causing a drop of up to another factor of 2 in the received scattered flux, or $\sim L_\star/32$ (see Fig. 4b). When the inclination increases further, the light of the star will start to be blocked (i.e. absorbed and therefore also reddened) by the near side of the disc, but at the same time also a portion of the far side of the disc is partly blocked, namely the portion closest to the star, thereby further decreasing the fraction of stellar light effectively scattered towards the observer (Fig. 4c). In the case of a perfectly edge-on disc, that fraction drops to zero for the opaque disc considered here, but in a more general case we can assume a drop by a factor of at least 2. This brings the total amount of light reflected by the disc towards the observer to $\lesssim L_\star/64$ and, with the star no longer directly visible (i.e. completely attenuated by extinction). It is only at this stage that the colours of the object at optical wavelengths will appear significantly bluer than those of the photosphere. However, it must be clear that at this point the brightness of the object is considerably less than when it is seen at low inclination, i.e. about 4.5 mag fainter.

In summary, this order of magnitude example shows that while at optical wavelengths the light received from a star may be made bluer than the intrinsic photospheric colours, the main effect of increasing the disc inclination is to make the star appear much fainter and progressively redder, because of extinction, before becoming blue. Therefore, if the BWE objects in Fig. 2 were RWE stars with discs seen at high inclination, they should be considerably fainter than the much more numerous RWE stars seen at low inclination. As Fig. 2 already suggests, there are simply not enough bright RWE objects for this to be the case. This deficiency is quantified in the following section.

6.2 Detailed model analysis

Robitaille et al. (2006) have computed a grid of radiation transfer models of young stellar objects (YSOs), covering a wide range of stellar masses, evolutionary stages, as well as envelope and disc parameters. The latter take into account theoretical and observational constraints on the physical conditions of discs and envelopes in YSOs, including parameters such as the outer radius, accretion rate and opening angle of the envelope, the mass, inner radius and flaring angle of the disc (see Robitaille et al. 2006 for details). These models provide the spectral energy distributions for ∼20 000 models, each of which is computed for 10 different viewing angles (i.e. disc inclinations), for a total of over 200 000 different realizations. These models can be used to illustrate numerically how the effects of disc inclination progressively alter the colour and magnitude of stars in the optical CMD.

We have selected from the grid of models a representative sample of objects with masses of 0.25, 0.5, 1, 2, 3, 4 and 8 $M_\odot$ and an age of 1 Myr, since this is the median age of NGC 6611 as determined by Guarcello et al (2010b). Note that since the grid is produced using a Monte Carlo radiation transfer code, it is usually not possible to select objects with a specific mass or age, so we have extracted all objects with ages within 1 per cent of 1 Myr and with masses within 20 per cent of the stated values. These small age and mass dispersion have no effects on our conclusions and, instead, they allow us to probe different regions of the parameter space, e.g. different disc opacities. As mentioned above, for each model the grid of Robitaille et al. (2006) provides the spectral energy distribution, including broad-band colours, for 10 different viewing angles, from almost pole-on ($\theta = 18^\circ$) to almost edge-on ($\theta = 87^\circ$), in equal intervals of cosine of the inclination angle θ.

In Fig. 5(a), we show where these objects are located in the CMD and how their colours and magnitudes change with disc inclination because of the effects of disc absorption (i.e. reddening) and scattering. The ordinates on the left-hand side refer to a distance modulus $m - M = 11.2$, as appropriate for NGC 6611, while the ordinates on the right-hand side provide the absolute V-band magnitude of the objects, M_V. The small grey dots show all model realizations for objects less massive than 8 $M_\odot$ and with ages in the interval 0.3–2.6 Myr, which is the age range derived by Guarcello et al. (2010b) for this cluster. There are a total of ∼30 400 models satisfying these conditions in the grid. The thick symbols in Fig. 5(a) identify the seven representative mass classes mentioned above. The large circles correspond to the lowest inclination angle ($\theta = 18^\circ$) and the crosses to the highest (87°), with intermediate angles indicated by dots. Note that in most cases only the point corresponding to the next-to-last angle can be seen, i.e. $\theta = 81^\circ$, since for all others the colour and magnitudes are practically indistinguishable from those of the face-on configuration. The dashed line in Fig. 5(a) indicates the ZAMS from Marigo et al. (2008) for solar metallicity,

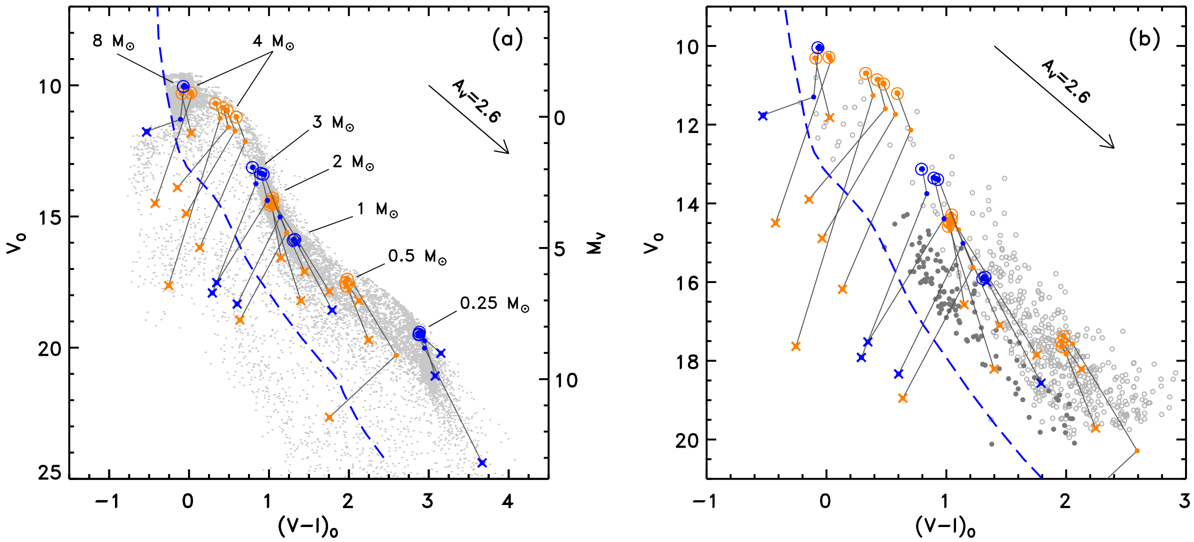

Figure 5. Panel (a): Synthetic CMD obtained from the models of Robitaille et al. (2006) for an age of ∼1 Myr and distance modulus 11.2. The grey small dots show all ∼30 400 model realizations with ages in the range 0.3−2.6 Myr and masses less than 8 $M_{\odot}$, whereas the thick symbols correspond to seven representative mass classes extracted from the grid, as indicated. For each mass class, we show the displacement of the models as a function of the inclination of the discs from almost face-on (large circles, $\theta = 18°$) to almost edge-on (crosses, $\theta = 87°$). Panel (b): The models of panel (a) are compared with the CMD position of BWE stars (dots) and RWE stars (circles). The dashed line in both panels is the ZAMS of Marigo et al. (2008) as in Fig. 2.

whereas the arrow shows the direction of the reddening vector for $A_V = 2.6$.

As mentioned in the previous section, when the inclination angle θ increases, there is in all cases first and foremost a dimming and a displacement towards redder colours, along the reddening vector. Only when the angle exceeds ∼85° one may find a possible shift to the blue, while for angles smaller than ∼85° the $V-I$ colours are systematically redder than those for a face-on configuration. Note, however, that not even for the highest inclination is the colour of the object necessarily bluer than at face-on conditions, since if the opacity of the disc is not enough to attenuate the radiation of the central star by a large factor, the scattered light does not dominate the object's $V-I$ colour. Conversely, if the discs were systematically thicker and more flared than assumed in the models of Robitaille et al. (2006), the effects of scattering would make these objects appear even bluer. However, as mentioned above, the parameter values sampled by these models directly span those determined from observations and theories, so such thicker discs would be unusual.

Fig. 5(a) also confirms that the order of magnitude calculations in Section 6.1 are correct, in that young PMS objects that appear near the MS because of scattering from a high-inclination disc are typically at least 4 to 5 mag fainter than the same objects seen at a lower ($\theta < 80°$) inclination angle.

In summary, we find that: (i) the main effect of a disc at high inclination is to dim the light from the star and to redden its colours; (ii) only for less than 10 per cent of the cases (corresponding to extremely high inclinations, i.e. $\theta > 85°$) is it possible that the observed colour become bluer than that of the star with a disc seen face-on; and (iii) in such rare cases, the 'bluer' stars will appear as sources that are several (say, 4 to 5) magnitude fainter than their intrinsic photospheric brightness.

Therefore, if the BWE stars in NGC 6611 were in reality young PMS stars like the RWE objects that appear blue only because of a high-inclination disc, the corresponding objects with discs seen at low inclination must be considerably brighter and, at the same time, much more numerous. This is because, as mentioned above, for $\cos\theta > 0.1$, i.e. for angles smaller than $\theta = 84°$, the $V-I$ colours are systematically redder than those for a face-on configuration. Therefore, the objects for which disc scattering dominates can be at most 10 per cent of the total population (recall that when the opacity of the disc is low the model does not veer to the blue in Fig. 5 even for the highest value of θ).

The implications of this conclusion can be seen graphically in Fig. 5(b), where the same models shown in panel (a) are overplotted on the CMD of NGC 6611. The grey circles are used for RWE stars and dark dots for BWE objects. The median colours and magnitudes of BWE stars are, respectively, $V-I = 1.1$ and $V = 16.6$, whereas for RWE stars the corresponding values are $V-I = 1.9$, $V = 17.8$ and as such they are typically fainter than BWE stars. This already indicates that BWE stars are in general not RWE stars with discs seen almost edge-on, since if that were the case, for every BWE stars there should be more than 10 RWE objects several magnitudes brighter so that the median V magnitude of RWE stars should be brighter and not fainter than that of BWE objects.

As an example, there is a large group of BWE stars, comprising approximately 50 objects, with $(V-I)_0 \simeq 1$ and $15 \lesssim V_0 \lesssim 17$. If these were RWE objects seen at high disc inclination, according to the models there should be in excess of 500 RWE stars with $V-I > 1$ and $V < 13$, whereas only a handful of objects are actually seen in that region of the CMD (note that further increasing the reddening correction of BWE stars would not reduce this discrepancy). Therefore, from a statistical point of view, only few of the BWE objects (particularly amongst those brighter than $V_0 \simeq 17$), can be stars whose light is affected by a high inclination disc, while for the majority of BWE objects the position in the reddening corrected optical CMD reliably reflects photospheric colours.

7 DISCUSSION

The analysis described in the previous sections allows us to establish with a high level of confidence that BWE and RWE objects belong to populations that are physically different. We summarize here the most important differences, all of which point to a systematic age difference between the two classes of objects.

(i) By definition, BWE and RWE objects are equally likely candidate disc-bearing objects associated with the Eagle nebula, but they occupy different regions of the optical CMD. No reasonable assumptions on the amount of extinction or on the extinction law can make the colours and magnitudes of BWE stars agree with those typical of RWE stars. Furthermore, although the blue $V - I$ colours of BWE stars could in principle be displayed by YSOs with a circumstellar disc seen at high inclination, this scenario can only apply to a handful of objects (10 per cent at most), since it requires both a very high disc inclination ($\theta > 85^\circ$) and high disc opacity. Also optical veiling, as shown by Guarcello et al. (2010a), can only be invoked in just a few cases to explain the blue colours of these stars. Spectroscopic observations confirm that strong veiling is infrequent (Bonito et al. 2013). For all other BWE objects, the most natural explanation of their blue colour is an age older than that of RWE stars. Isochrone fitting suggests an age more than an order of magnitude older than that of the young PMS stars first discovered by Hillenbrand et al. (1993). Assuming the literature age of ∼1 Myr for the young PMS stars (e.g. Hillenbrand et al. 1993; Bonatto, Santos & Bica 2006; Guarcello et al. 2007, 2010b), for the BWE objects we obtain an age of ∼16 Myr to within a factor of 2.

(ii) The radial distributions of RWE and BWE objects are very different. Although they share the same centre (to within 1 arcmin), RWE objects are strongly concentrated while BWE stars are more widely and uniformly distributed, with a core radius about three times larger (∼3 arcmin versus ∼1 arcmin). Note that this also rules out that BWE objects are due to mismatches between foreground stars and background NIR sources, since these would be more likely in the central regions of the cluster, where the density of optical sources is higher. The presence of accretion witnessed by the wide Hα emission lines in at least half of the BWE objects studied spectroscopically further excludes the case of mismatches. A Kolmogorov–Smirnov test shows that the cumulative radial distributions of the two populations of BWE and RWE stars are significantly different, at the level of 10^{13}. An older age for the BWE stars would explain their wider spatial distribution.

(iii) The X-ray properties of RWE and BWE stars are also very different. Only 6 per cent of the BWE stars are detected in the X rays above the detection threshold of $\log L_X = 29.8$ erg s^{-1}, while for RWE objects this fraction is 46 per cent. The X-ray luminosity of PMS stars is known to decrease with stellar age, so an older age for the BWE stars would explain their lower median L_X. Assuming an X-ray luminosity distribution similar to that of PMS stars in Orion, the remarkably different fraction of stars with X-ray detection requires an age difference larger than 10 Myr, in agreement with the isochronal ages mentioned above.

Each of these three major differences represents a necessary condition for an age discrepancy between BWE and RWE objects. Taken individually, they may not be sufficient conditions, but the fact that they occur simultaneously leaves little doubt that an age difference is effectively present. Had BWE stars the same age as RWE objects, in order to appear bluer they would all need to have a high inclination circumstellar disc. In addition, one should require a correlation of the spatial distribution of disc inclinations with the X-ray luminosity of these objects: all of these conditions appear exceedingly contrived.

One could imagine other effects that would change the age estimate of BWE stars, but none of them can affect the ages of BWE stars without affecting in a comparable way those of RWE stars. For instance, the effects of unaccounted binaries on age estimate of PMS stars have been discussed in detail by Naylor (2009) and Da Rio, Gouliermis & Gennaro (2010), who show that neglecting unresolved binaries may lead to an underestimation of the age of all PMS stars of a young cluster by a factor of 1.5−2.

An older age for the BWE objects is also consistent with the recent spectroscopic observations at intermediate spectral resolution ($R = 17\,000$) carried out by Bonito et al. (2013) for a sample of 20 stars with FLAMES at the Very Large Telescope over the range between 6470 and 6790 Å. These authors find that BWE objects typically lack a strong Li absorption line at 6708 Å, which is an indicator of youth in PMS stars (e.g. Barrado y Navascués, Stauffer & Jayawardhana 2004); only five of these objects have EW(Li) > 0.1 Å and only three of them have EW(Li) > 0.3 Å. At the same time, at least half of the BWE stars exhibit a strong and asymmetric Hα emission line, with absorption features and typical line widths of $\gtrsim$200 km s^{-1} revealing active mass accretion.[3]

Therefore, the most logical conclusion is that the main difference between RWE and BWE objects is age, with the important consequence that star formation must have been active in this field over a period of at least 20–30 Myr. Guarcello et al. (2010b) show that the stars born in the most recent formation episode, i.e. the RWE objects, have a median age of ∼1 Myr, ranging from 0.3 to 2.6 Myr. Isochrone fitting to the BWE objects in the CMD of Fig. 2 suggests an age of ∼16 Myr to within a factor of 2 for those objects, i.e. ages ranging from ∼8 to ∼32 Myr for the majority of them. Note that this age range does not necessarily imply that star formation has proceeded continuously over that period of time, but it rather reflects the limitations in our age resolution, since current uncertainties on the photometry, on the reddening correction and on the PMS models do not allow us to resolve ages to better than a factor of ∼2. Thus, it is possible that more than one burst of star formation had contributed to the population of BWE stars, but we cannot distinguish them from one another as clearly as we can separate RWE from BWE objects.

Concerning the chronology of star formation in M 16, with an age approximately between 15 and 30 Myr, the BWE stars must predate the formation episode that started some ∼3 Myr to the southeast of NGC 6611 and that propagated towards northwest. Guarcello et al. (2010b) have tentatively identified this event in the incidence of a giant molecular shell (Moriguchi et al. 2002), created some 6 Myr ago by supernova explosions. With ages of the order of 15–30 Myr, BWE stars clearly predate these events and they probably have nothing to do with the birth of the RWE stars between 3 and 0.3 Myr ago.

NGC 6611 is not the only cluster in which multiple generations of PMS stars are seen. In the Milky Way, recent observations clearly show that the star formation in NGC 3603 has slowly progressed over the past ∼30 Myr across the entire cluster (Beccari et al. 2010; Correnti et al. 2012). In the Magellanic Clouds, a similar star formation pattern has been seen in 30 Dor and neighbouring regions (De Marchi et al. 2010, 2011a; Spezzi et al. 2012), in NGC 346 (De Marchi, Panagia & Sabbi 2011b; De Marchi et al. 2011c) and in NGC 602 (De Marchi, Beccari & Panagia 2013). But while in all these regions PMS stars (young and old) are identified thanks to

[3] Note that, although in principle also interacting binaries would have similarly prominent *H*α emission and NIR excess (e.g. Warner 1995), objects of this type are very rare: they represent only ∼3 per cent of all the stars in the IPHAS catalogue of Hα emission line sources in the northern Galactic plane for which spectroscopy is available (Witham et al. 2008). As such, their contribution to our sample is negligible.

their Hα excess emission, in NGC 6611 the signature of the PMS phase is the presence of a circumstellar disc revealed by the NIR excess.

In fact, in the Milky Way, NGC 6611 hosts what is presently the largest population of candidate disc-bearing stars older than ∼10 Myr and as such it allows us to set much stronger constraints on the disc fraction at this late stage of PMS evolution than it was possible so far (see Section 1). The oldest cluster in which a proper measurement (i.e. excluding non-detections) of the disc fraction exists from NIR and Hα excess is NGC 7160, studied by Sicilia-Aguilar et al. (2006). The disc fraction that these authors derive is actually an upper limit in the 2–4 per cent range, but it is based on just three objects and, as such, it is very uncertain. In the case of NGC 6611, the observations discussed in this paper provide a much higher statistical accuracy.

As mentioned in Section 3, the Besançon models of Galactic population synthesis (Robin et al. 2003) predict a total of 367 contaminating field stars inside the dotted box in Figs 1 and 2 over the whole field of view and out to distances of 50 kpc for the direction of M 16. Therefore, it appears that of the 1444 stars in that region of the CMD (shown in Fig. 1 as small grey dots), only 1077 are likely cluster members.

This means that in NGC 6611 the disc fraction for objects older than ∼8 Myr and younger than ∼32 Myr (median age ∼16 Myr) is at least 7 per cent. In fact, this fraction is still a lower limit since the probable cluster members may include a substantial number of stars older than 32 Myr. In any case, a disc frequency of 7 per cent or higher at an age of ∼16 Myr implies a characteristic exponential decay time-scale for disc dissipation of ∼6 Myr, assuming an initial fraction of 100 per cent. This time-scale appears appreciably longer than the 3 Myr estimated by Fedele et al. (2010) from the analysis of a compilation of nearby clusters with published disc frequencies based on NIR excess measurements. However, our result is fully consistent with the upper limits that Fedele et al. (2010) derived for older regions and with the observations of h and χ Per by Currie et al. (2007a) and those of Sco–Cen by Chen et al. (2011) mentioned in Section 1. Furthermore, the semi-empirical PMS isochrones of Bell et al. (2013) also suggest circumstellar disc lifetimes about twice as long as currently believed.

The apparent difference between our result and that of Fedele et al. (2010) may be ascribed to small number statistics (both in the number of clusters and old stars considered in each cluster) in the sample compiled by those authors. NGC 6611, instead, being a more massive cluster, has a large population of PMS stars with NIR excess (i.e. candidate disc-bearing objects) also at ages in excess of ∼10 Myr and this permits more robust statistics. Besides h and χ Per and Sco–Cen just mentioned, a similar case of relatively massive cluster is Trumpler 15, whose stars reveal a disc frequency of ∼4 per cent (Wang et al. 2011) at ages ranging from 4 to 30 Myr, with a median of 8 Myr (Tapia et al. 2003).

We cannot of course rule out that the disc fraction that we obtain in NGC 6611 would drop slightly if the contamination by foreground and background stars were much lower than suggested by the Galactic models of Robin et al. (2003), who indeed warn that at low Galactic latitudes model uncertainties are larger. But even in the extreme case of no foreground or background contamination, the disc fraction in NGC 6611 would remain above the firm lower limit of 3.8 per cent, implying a characteristic exponential decay time-scale of at least 4.9 Myr.

There might be other more physical effects causing the observed differences, which could be related to the different environmental conditions prevailing in low-mass nearby star-forming regions and in high-mass star clusters elsewhere in the Milky Way and beyond. For instance, as mentioned in Section 1, the proximity of massive OB-type stars is known to enhance the disruption of circumstellar discs by photoevaporation, an effect which is directly observed also in NGC 6611 (Guarcello et al. 2010b), as well as in Orion (e.g. Mann & Williams 2010) and in the LMC (De Marchi et al. 2010). This effect will reduce the observed disc fraction as time goes by, but the denser interstellar medium needed to form massive stars in these regions implies that the efficiency of photoevaporation process is also reduced. Therefore, PMS stars formed more than 8 Myr earlier that have had enough time to move away from massive objects could have retained a larger fraction of their discs.

In any case, these observations underline the importance of investigating the properties of PMS stars not only in nearby regions of diffuse star formation such as Taurus–Auriga and ρ Ophiuchi, but also in more distant and massive starburst clusters. This will be necessary to secure a more complete and realistic picture of the physics governing the star formation process, if it is true (e.g. Lada & Lada 2003) that the majority of stars in the Milky Way, including those in the solar neighbourhood, have formed in rich clusters containing massive (>8 $M_\odot$) O-type stars.

8 SUMMARY AND CONCLUSIONS

We have studied in detail the population of 110 stars with prominent NIR excess and rather blue $V-I$ colours, discovered by Guarcello et al. (2010a) in NGC 6611, by comparing them to the ∼4 times more numerous stars with NIR excess and red $V-I$ colours typical of young PMS stars. The main results of this work can be summarized as follows.

(i) We show that, besides occupying different regions in the CMD, the BWE stars and RWE stars have rather different physical properties. These include differences in the spatial distribution (with RWE objects being much more centrally concentrated than BWE stars) and in the X-ray luminosity (with only 4 per cent of the BWE stars being detected above $\log L_X = 29.8$ erg s^{-1} versus 46 per cent of the RWE objects). Each of these three major differences represents a necessary condition for BWE objects to be considerably older than RWE stars. The fact that these conditions occur simultaneously leaves little doubt that an age difference is effectively present and that BWE and RWE stars belong to two distinct classes of objects. An additional indication of an older age for the BWE stars comes from their relatively weak or absent Li absorption lines. Through comparison with PMS isochrones for stars of solar metallicity, we derive ages in the range 8−32 Myr for most BWE stars, with a median age of 16 Myr.

(ii) Actually, a very small number of BWE stars could in fact be RWE objects that appear bluer in $V-I$ because of optical veiling or because of a circumstellar disc seen at very high inclination. However, the largest majority of them cannot be objects of this type for the following reasons: (1) the main effect of a disc at high inclination is to dim the light from the star and to redden its colours; (2) only for extremely high inclinations ($\theta > 85°$), and hence very rarely, can the observed colour become bluer than that of the same star seen with a face-on disc; and (3) in such rare cases, the bluer stars will appear at least 4 to 5 mag fainter than their intrinsic photospheric brightness.

(iii) These observations provide us with the largest homogeneous sample to date of Galactic PMS stars considerably older than 8 Myr that are still actively accreting from a circumstellar disc as witnessed by the ∼200 km s^{-1} wide Hα emission lines in the spectra of a sample of these objects. Such a large number of disc-bearing candidates with a median age of ∼16 Myr in NGC 6611 allows us to set a lower limit of 7 per cent to the disc frequency in this cluster, with high statistical significance. Assuming an initial fraction of 100 per cent at birth, these values in turn imply a characteristic exponential time-scale for disc dissipation of ∼6 Myr.

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SUPPORTING INFORMATION

Additional Supporting Information may be found in the online version of this article:

Table 1. Photometric catalogue, listing the ID number, equatorial coordinates (J2000), *V* and *I* magnitudes with their uncertainties and whether the object was detected in the X rays (Y = yes, N = no, while O indicates that the object is outside the field covered by the X-ray observations) (http://mnras.oxfordjournals.org/lookup/suppl/doi:10.1093/mnras/stt1499/-/DC1).