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# Is stellar multiplicity universal? Tight stellar binaries in the Orion nebula Cluster

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## ABSTRACT

We present a survey for the tightest visual binaries among  $0.3\text{--}2 M_{\odot}$  members of the Orion nebula Cluster (ONC). Among 42 targets, we discovered 13 new  $0.025\text{--}0.15$  arcsec companions. Accounting for the Branch bias, we find a companion star fraction (CSF) in the  $10\text{--}60$  au range of  $21^{+8}_{-5}$  per cent, consistent with that observed in other star-forming regions (SFRs) and twice as high as among field stars; this excess is found with a high level of confidence. Since our sample is dominated by disc-bearing targets, this indicates that disc disruption by close binaries is inefficient, or has not yet taken place, in the ONC. The resulting separation distribution in the ONC drops sharply outside 60 au. These findings are consistent with a scenario in which the initial multiplicity properties, set by the star formation process itself, are identical in the ONC and in other SFRs and subsequently altered by the cluster's dynamical evolution. This implies that the fragmentation process does not depend on the global properties of a molecular cloud, but on the local properties of prestellar cores, and that the latter are self-regulated to be nearly identical in a wide range of environments. These results, however, raise anew the question of the origin of field stars as the tight binaries we have discovered will not be destroyed as the ONC dissolves into the Galactic field. It thus appears that most field stars formed in regions that differ from well-studied SFRs in the solar neighbourhood, possibly due to changes in core fragmentation on Gyr time-scales.

**Key words:** binaries: visual – stars: pre-main-sequence – open clusters and associations: individual: Orion Nebula Cluster.

## 1 INTRODUCTION

The ubiquity of stellar multiplicity in the youngest stellar populations has been long established, proving that this is an inherent feature of the star formation process itself (Duchêne & Kraus 2013, and references therein). In order to constrain the mechanism through which multiple systems form, searches have been conducted to identify trends in multiplicity properties besides the strong dependency on primary stellar mass which is generally well reproduced by a wide range of models (e.g. Delgado-Donate, Clarke & Bate 2004; Goodwin, Whitworth & Ward-Thompson 2004; Moeckel & Bate 2010; Bate 2012).

Much like studies of the initial mass function, one focus has been on the hunt for significant differences between the multiplicity

properties of different stellar populations. From the earliest studies of populations of T Tauri stars, it was clear that visual binaries are twice as common in nearby SFRs as they are among field stars of similar masses at separations ranging from tens to thousands of au (Duchêne 1999, and references therein). However, this high occurrence of visual companions is not universal, as it was later found that stellar populations in young clusters are characterized by a field-like multiplicity rate. This was reported both for open clusters (e.g. Bouvier, Rigaut & Nadeau 1997; Patience et al. 1998) and young clusters still associated with their parent molecular cloud (e.g. Padgett, Strom & Ghez 1997; Petr et al. 1998; Duchêne, Bouvier & Simon 1999). This is especially true in the Orion nebula Cluster (ONC) which has been targeted by several multiplicity surveys of increasing resolution, scale, and sensitivity (Petr et al. 1998; Köhler et al. 2006; Reipurth et al. 2007; Kounkel et al. 2016) and is the focus of this study. There are virtually no binary systems in the ONC whose semimajor axis is larger than 1000 au (Sclally, Clarke & McCaughrean 1999).

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† The observations presented here were obtained as part of ESO program ID: 096.C-0270.

This dichotomy of multiplicity frequency (field-like in stellar clusters, much higher in loose young associations) can be explained by two distinct scenarios; essentially this is a case of nature versus nurture. In one scenario, dense clusters simply form a much reduced number of wide systems due to intrinsic differences in how star formation proceeds in these environments, while the CSF (defined as the ratio of the number of companions to the number of targets) in loose associations approaches 100 per cent. The alternative is that all SFRs actually form binary systems with essentially universal characteristics but that are subsequently significantly altered by dynamical processes, such as intracluster encounters and decay of unstable high-order multiple systems (Goodwin et al. 2007, and references therein). Given the observations of loose associations, the initial conditions for multiplicity include a rate of visual binaries that is twice as high as that of field stars but many of the wider pairs could be susceptible to destruction in three-body interactions.

The debate between these two scenarios has been ongoing for over two decades. In short, it is reasonable to assume that the physics of star formation should differ in environments that lead to such different outcomes as a rich stellar cluster and a loose association (e.g. Sterzik, Durisen & Zinnecker 2003; Goodwin, Whitworth & Ward-Thompson 2004). However, disruption of wide binaries in dense clusters, if they actually form, is inescapable and can occur on very short time-scale ( $\lesssim 1$  Myr; see e.g. Kroupa 1995). Interestingly, the multiplicity properties of diverse environments such as the Taurus association and dense clusters such as the ONC and the Pleiades can be reproduced by assuming a universal set of multiplicity properties and allowing internal cluster dynamics to destroy some systems (Kroupa, Petr & McCaughrean 1999; Kroupa, Aarseth & Hurley 2001; Kroupa & Bouvier 2003). Whether this is the correct explanation, however, has been questioned by different groups (King et al. 2012; Marks et al. 2014; Parker et al. 2014). Different assumptions about the current and past dynamical states of stellar populations are at the heart of the ongoing debate, but these cannot be easily tested with current observations, which explains why the problem has been lingering for two decades.

Besides the implications for the star formation process, determining whether or not multiplicity properties are universal at birth has important ramifications for the topic of the origin of field stars. Indeed, while the population of field stars represents a mix of all modes of star formation in the Galaxy, the excess of visual companions among loose associations readily indicates that such SFRs cannot produce the majority of field stars. Under the universal multiplicity properties scenario outlined above, it is in principle possible to infer the typical stellar density of clusters that produce the majority of field stars in an inverse population synthesis approach (Kroupa 1995; Marks & Kroupa 2011) although, once again, uncertainties about the early dynamical evolution of clusters raise significant uncertainties (Parker et al. 2014).

As discussed above, the ONC has been one of the key stellar populations in solving this puzzle. However, its large distance ( $388 \pm 5$  pc, Kounkel et al. 2017) compared to other nearby SFRs (125–140 pc) has limited the projected separation range probed by past multiplicity surveys to  $\gtrsim 60$  au ( $\gtrsim 0.15$  arcsec). Most binaries at these large separations are liable to destruction within the first few Myr of the cluster’s evolution but, given our current understanding of the past history of the ONC, tighter binaries should be sufficiently tightly bound so as not to be severely affected (Kroupa et al. 1999; Parker et al. 2009). In other words, the multiplicity properties of systems tighter than 60 au should be pristine even in the ONC. This enables an immediate test of the universality hypothesis, since under that scenario, one would expect to find the same companion fraction

in the ONC as in other SFRs. That fraction would be roughly twice as high as that of field stars, as indicated by observations in various, non-clustered SFRs (King et al. 2012). Measuring the CSF over the same separation range in the ONC is the goal of this study.

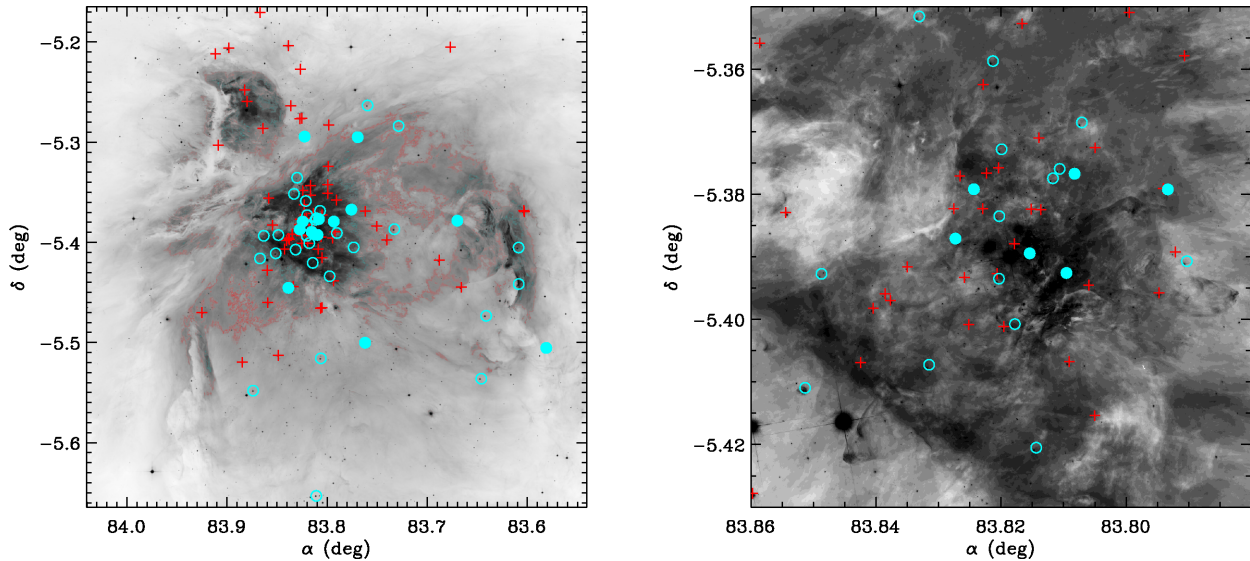
The fundamental limit of past multiplicity studies of the ONC was angular resolution, which was set by the diffraction limit of the instruments in use. Searches with both the *Hubble Space Telescope* (*HST*) at visible wavelength and large ground-based telescope in the near-infrared are limited to companions outside of 0.1–0.15 arcsec in order to be sensitive to stellar companions of all masses and not just to equal-mass binaries (and even then, only if the separation exceeds  $\lambda/D$ , where  $\lambda$  is the observing wavelength and  $D$  is the telescope diameter). In this study, we take advantage of the aperture masking technique to reach the highest resolution on monolithic telescopes and find tighter companions than previous studies. By virtue of the simplicity of the signal introduced by a binary in this interferometric observations, it is possible to detect and characterize companions down to separations of  $\lambda/2D$ , or about 0.025 arcsec at  $2 \mu\text{m}$  on an 8-m telescope (see e.g. Lacour et al. 2011). At the distance of the ONC, it is therefore possible to detect companions down to projected separations as small as 10 au. This same technique has been used in the past to probe stellar companions down to 2–5 au in several nearby SFRs (e.g. Kraus et al. 2011; Cheetham et al. 2015).

The outline of this paper is as follows: we present the sample selection, observations, and data reduction in Section 2, present the results of our survey in Section 3, and discuss them in Section 4.

## 2 SAMPLE AND OBSERVATIONS

### 2.1 Sample selection

The sample was built from the ONC catalogues of Hillenbrand (1997, hereafter H97), Hillenbrand et al. (1998), and Hillenbrand, Hoffer & Herczeg (2013). From all objects in these catalogues, we first selected a magnitude-limited sample using the range  $7.5 \leq K \leq 9.5$ . The faint limit is set by a signal-to-noise requirement for successful aperture masking measurement given short exposure integrations. The bright end was chosen to avoid high-mass stars and to ensure that each target would have at least two other targets of similar magnitude that can serve as calibrators. From this list, we discarded objects with spectral types earlier than G0, again to remove stars more massive than  $\approx 2 M_{\odot}$ . Finally, objects whose membership probability is less than 50 per cent (Hillenbrand 1997; Bouy et al. 2014) were eliminated. At this stage, we retained objects with unknown probability as likely members until proven otherwise; two of those (H97 3109 and H97 3131) were subsequently confirmed as cloud members by Fűrész et al. (2008). This yielded our initial sample of 109 targets distributed throughout the ONC, with distances from  $\theta^1$  Ori C ranging from 7 arcsec to 17 arcmin, i.e. about 2 pc (see Fig. 1). From the initial sample, we observed 42 targets with NaCo-SAM, as well as 4 objects with membership probability lower than 50 per cent, which we report here for completeness but do not include in our analysis. The basic properties of all observed targets are listed in Table 1. A few targets were known subarcsecond binaries and/or spectroscopic binaries from past surveys (Tobin et al. 2009; Robberto et al. 2013), although we note that none of these companions could be detected in our aperture masking survey. Figs 1 and 2 illustrate the spatial distribution of the initial and observed samples, while Fig. 3 presents the  $K$ -band brightness distribution of these samples.



**Figure 1.** Spatial distribution of the observed (circles) and unobserved (red crosses) subsamples. Filled (open) circles indicate objects that were found to have one (no) companion in the separation range probed by the aperture masking observations (i.e. separation  $\leq 0.2$  arcsec). The right-hand panel is a zoom on the centre of the cluster. In both cases, the underlying grey-scale image is the *HST* *r*-band image from Robberto et al. (2013).

Estimating masses in the ONC population is a notoriously non-trivial issue because of crowding, confusion with the surrounding nebula and large and inhomogeneous line-of-sight extinction. As a result, while many stars in our initial sample have multiple mass estimates in the literature (e.g. Hillenbrand 1997; Da Rio et al. 2010; Manara et al. 2012; Da Rio et al. 2016; Kim et al. 2016), there are differences up to a factor of 3 between the various estimates. Stellar masses should thus be considered with circumspection. To minimize sources of biases, we adopted masses from Da Rio et al. (2016), Da Rio et al. (2010), Kim et al. (2016), and Manara et al. (2012), which all use the Siess, Dufour & Forestini (2000) evolutionary model, in that order of priority. Only 11 targets in the initial sample, and only one of our observed target, has no mass estimate. As shown in Fig. 4, the flux-limited selection results in an initial sample that is not representative of the IMF in the ONC but is heavily biased towards stars more massive than the Sun. To focus our analysis around solar-type stars, the observed sample was selected to be less dominated by intermediate-mass stars than the initial sample. The median mass in the observed sample is  $0.8 M_{\odot}$ , with 16 and 84 percentile at 0.4 and  $1.6 M_{\odot}$ , respectively. Thus, our sample is dominated by solar-type stars, albeit with the addition of a few lower and higher mass stars. About 75 per cent of our sample consists of K-type T Tauri stars and only one observed cluster members (H97 613) has  $M_{*} > 2 M_{\odot}$ .

Finally, we used literature information to assess which of our targets possess a circumstellar disc. Specifically, we consider that a star has a disc if its SED displays significant infrared excess (Hillenbrand et al. 1998; Megeath 2012), if its optical spectrum reveals a strong and/or broad  $H\alpha$  emission, or the infrared Ca triplet in emission (Hillenbrand et al. 1998; Sicilia-Aguilar et al. 2005; Fűrész et al. 2008; Da Rio et al. 2009; Manara et al. 2012; Szegedi-Elek et al. 2013; Kim et al. 2016), or if it has an estimated accretion rate (Da Rio et al. 2010). In cases where multiple indicators of the presence of circumstellar material are available, they are in agreement with one another. The lone exception to this statement is H97 567, which has no significant *K*-band excess (Hillenbrand et al. 1998), yet displays strong  $H\alpha$  emission and significant Ca triplet emission (Hillenbrand et al. 1998; Da Rio et al. 2009). We

consider that this system likely has a disc but that its near-infrared excess is too weak to be detected; no mid-infrared observations of the system are available. Of the 42 confirmed cluster members studied here, 32 are associated with a disc. Thus, our observed sample is characterized by a frequency of circumstellar discs that is consistent with the observed rate of 60–80 per cent in the overall ONC population (Hillenbrand et al. 1998; Lada et al. 2000).

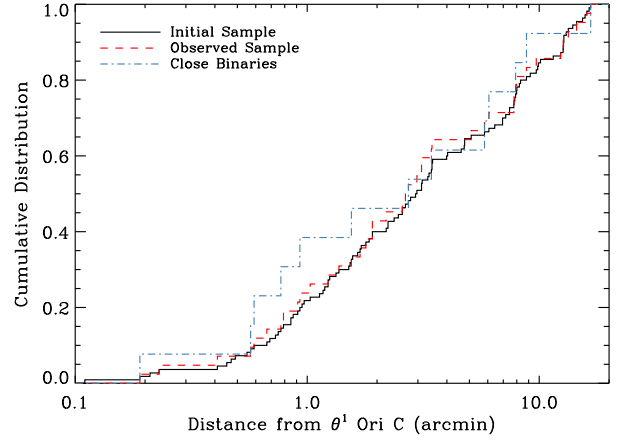
## 2.2 Observations and data reduction

We conducted our program with the NACO instrument on VLT/UT4. The observations were conducted over five half-nights in 2016 January scheduled in two separate runs during programme 096.C-0270. All observations were made using the S13 camera ( $0.01322$  arcsec pixel $^{-1}$ ), with the  $K_s$  filter and the seven-hole mask (Tuthill et al. 2010). Because some of our targets are faint in the visible and due to confusion from the bright nebula associated with the ONC, we used the infrared wavefront sensor mode of NACO with the N90C10 entrance dichroic to obtain optimal adaptive optics performance.

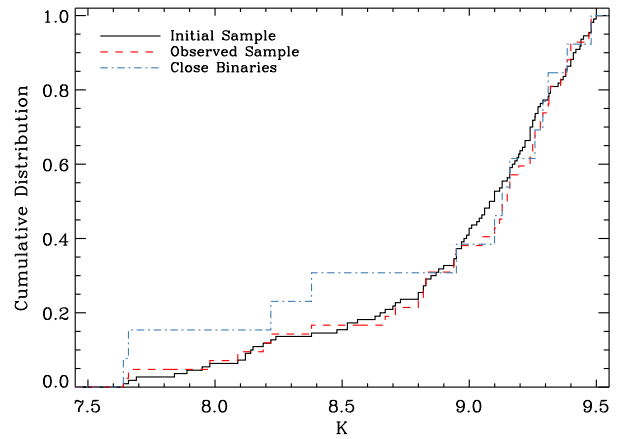
Targets were associated in groups of four to nine objects based on their magnitude and sky position in order to generate observations sequences. With this set-up, the adaptive optics parameters were set on the first target and maintained fixed from object to object, enabling rapid switching between targets. This ensures a high survey efficiency, as observing multiple science targets in rapid succession removes the need of including dedicated (single) calibrator stars. Instead, all objects found to be single stars in each sequence can serve as calibrators for the other targets. During each half-night, we executed one to three such observing sequences. In the last three half-nights, observations of some possible candidate binaries were repeated to confirm their nature, as were observations of clearly single stars that were used to serve as safe calibrators. All observing sequences are detailed in Table 2. Integration times of 30 to 120 s were used to ensure sufficient signal to noise in individual frames. Three data cubes of four or six such frames were acquired with 3–4 arcsec dithers between each cube to enable sky subtraction and bad

**Table 1.** Observed sample.  $K$  magnitudes are from the 2MASS Point Source Catalog. Spectral types and masses are from Hillenbrand (1997) and Da Rio et al. (2016), respectively, unless otherwise noted. Additional references: <sup>a</sup>Hillenbrand et al. (2013), <sup>b</sup>Da Rio et al. (2010). The fifth and sixth column indicate whether the object possess signs of accretion and a circumstellar disc, respectively (see Section 2.1). In a few cases, accretion indicators are ambiguous; those are indicated by a ‘?’ qualifier. The last column indicates which target was previously known to be a visual binary with separation in the 0.2–1 arcsec range (Robberto et al. 2013) or is a known spectroscopic binary (Tobin et al. 2009).

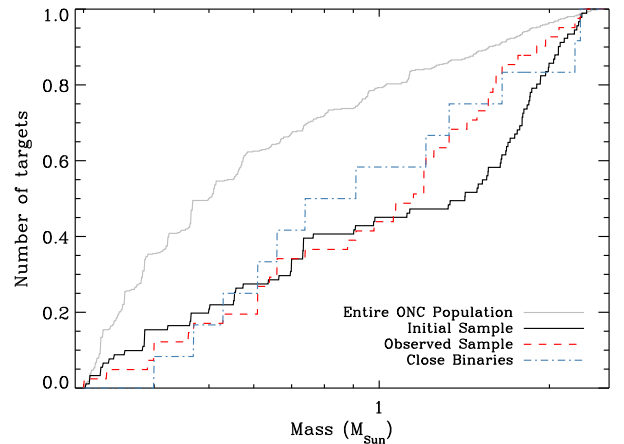
H97	$K$	Sp.T.	$M(M_{\odot})$	Disc?		Mult.
				Acc.	IR	
Cluster members						
27	9.36	K2	1.43	N	N	
29	9.39	K2	1.49	N	N?	
50	8.60	K1	0.66	Y	Y	SB2
150	9.30	K4–5 <sup>a</sup>	0.66	Y	Y	
157	8.06	K2	1.15	N	N	
221	8.01	K3	1.61	N	N	
232	9.22	K1–2	0.61	Y?	Y	
253	9.34	K8 <sup>a</sup>	0.91	Y?	Y	0.27 arcsec; SB2
278	9.32	K2–7	0.98 <sup>b</sup>	Y	Y	
286	9.14	K5	1.33	Y	Y	
337	9.43	K8	0.64 <sup>b</sup>	Y?	Y	
345	9.43	M0.5	0.40	Y	Y	
365	8.74	K2–3	0.88	N	N?	
421	8.62	K5	1.17	Y	Y	
423	8.86	K2	0.39 <sup>b</sup>	Y	Y	
432	9.25	M3.1	0.33 <sup>b</sup>	Y?	Y	
441	9.27	M1	0.37	Y?	Y	
448	9.14	K7	0.74 <sup>b</sup>	Y	?	
454	8.66	K4	1.56 <sup>b</sup>	Y	Y	
460	8.80	K0–3	1.59	Y	Y	
478	8.73	M0.4	0.57	N	N?	
488	8.37	K1	1.33 <sup>b</sup>	Y	Y	
515	8.61	K4–7	...	Y	Y	
529	9.36	M0	0.56 <sup>b</sup>	Y	Y	
533	9.42	M0	0.47	Y	Y	
534	9.23	M2	0.39 <sup>b</sup>	Y	Y	
544	8.19	K4–7	1.97 <sup>b</sup>	N	N	
550	8.21	K2–3	1.90	Y	Y	0.88 arcsec
567	7.58	K3–4	1.99 <sup>b</sup>	Y	N	
596	7.64	G5–K1 <sup>a</sup>	1.68	Y	Y	
613	9.04	K2	2.51	Y?	Y	
622	9.27	M0–2.5	0.37	Y	Y	
631	8.71	K7	1.08	Y	Y	SB2
683	9.40	K6	1.07	N	N	
744	9.37	M1 <sup>a</sup>	0.47 <sup>b</sup>	Y	Y	1.00 arcsec
756	8.91	M0	0.44	Y	Y	SB2
810	9.35	K4	0.62	Y	Y	
826	9.18	K5 <sup>a</sup>	0.77 <sup>b</sup>	Y	Y	
847	9.16	K3	1.25	N	N	
3085	9.22	K7	0.61	N	N	
3109	9.15	K2–3	0.61	Y	Y	
3131	9.45	K5	1.21	Y	Y	
Likely non-members						
4	9.43	K4	0.82	Y	Y	0.79 arcsec; SB1
45	7.95	K4	1.37	N	N	
351	8.79	G4–6	2.43	N	?	
413	8.16	K5	1.03 <sup>b</sup>	N	N?	



**Figure 2.** Cumulative distribution of distance to  $\theta^1$  Ori C for the initial sample (black solid histogram), the observed subsample (red dashed histogram), and the subset of all binaries with separation  $\leq 0.2$  arcsec (blue dot-dashed histogram).



**Figure 3.** Cumulative  $K$ -band brightness distribution of the initial sample, the observed subsample, and the subset of all binaries with separation  $\leq 0.2$  arcsec. Linestyles and colours are as in Fig. 2.



**Figure 4.** Cumulative distribution of masses for the initial sample, the observed subsample and the subset of all binaries with separation  $\leq 0.2$  arcsec. Linestyles and colours are as in Fig. 2. The mass distribution for the entire ONC is shown in grey for reference, based on the survey by Da Rio et al. (2010).

**Table 2.** Observing sequences executed during the course of this survey. Italicized targets represent non-members of the ONC.

Date (UT)	H97	DIMM seeing (arcsec)
01/16/2016	45, 157, 221, <i>413</i> , 488, 544, 550, 567, 596	1.56–2.15
01/17/2016	50, 365, 454, 478, 515, 631 <i>351</i> , 421, 488, 756	1.20–1.63 0.87–1.68
01/27/2016	4, 29, 337, 345, 533, 683, 3131	1.12–1.84
01/28/2016	27, 253, 278, 441, 529, 744, 810 150, <i>413</i> , 421, 515, 550, 567, 596	0.87–1.12 0.66–0.91
	232, 286, 432, 3085, 3109	0.71–1.09
	534, 622, 826, 847	0.71–1.09
01/29/2016	421, 423, 460, 478, 515, 756 432, 441, 448, 529, 622 221, 413, 544, 550, 613	0.67–0.77 0.84–0.96 1.08–1.26

pixel correction (except for H97 4 and H97 613, for which we only obtained two data cubes).

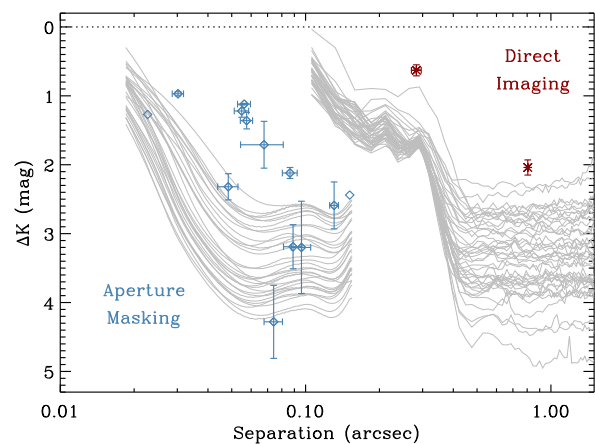
Data reduction involved the usual steps of flat-fielding, background subtraction and bad pixel correction. Analysis of the resulting data sets was performed in two steps. First, all images were aligned and median combined to produce ‘direct’ images. In these images, the Fizeau interference pattern induced by the mask is readily evident as a combination of distinct discrete peaks, but it is still possible to identify companions outside of  $\approx 0.25$  arcsec, whose position and brightness can be determined through a cross-correlation technique. Given the number of frames per target in our observing sequence, we achieve a  $5\sigma$  contrast in the 2.5–4 mag range.

To identify tighter systems, however, an interferometric analysis of the data is necessary, as the signature of a companion lies in the closure phase associated with the baselines defined by the mask. To this end, we use the SAMP pipeline (Lacour et al. 2011) which decomposes the interferometric pattern in a series of discrete spatial frequencies (each defined by a unique pair of holes) and computes the closure phases for each distinct triangle of holes from the corresponding bispectrum. Those closure phases, which should be null for a point source, are calibrated by subtracting the average closure phase observed for all single source in each observing sequence. We then fit a single star model and a binary system model to all data on a given target. The binary star model is selected only in cases where the  $\chi^2$  of the single star model is unacceptable. Otherwise, a map of the  $5\sigma$  detection limit is produced for each target. This results in a roughly separation-independent detection limit between 0.04 and 0.15 arcsec, where the outer search radius is set by the diffraction limit corresponding to the shortest spacing between the mask holes. The  $5\sigma$  sensitivity of our aperture masking survey ranges from 2.5 to 4 mag, similar to the sensitivity achieved by direct imaging at larger separation, as discussed above (see Fig. 5). At the closest separations, the detection limit degrades gradually down to  $\approx 0.02$  arcsec, inside of which sensitivity to companion vanishes in aperture masking.

### 3 RESULTS

#### 3.1 Detected companions

The observed properties of all companions are listed in Table 3. Inspection of the direct images revealed only two companions which had already been discovered in *HST* images of the ONC with relative

**Figure 5.** Detected companions and individual  $5\sigma$  detection limits for targets in our survey; targets with a detected companion within the range of separation of each method are excluded as their detection limit are significantly affected by the presence of a second point source. Blue diamonds and red asterisks represent companions detected by closure phase analysis and cross-correlation of direct images, respectively. Black diamonds mark two companions detected in the closure phase analysis but whose flux ratio is poorly estimated (see Section 3.1).**Table 3.** Close companions detected in this survey.

H97	$\rho$ (mas)	PA ( $^\circ$ )	$\Delta K$ (mag)
Closure phase analysis			
50 <sup>a</sup>	$151.3 \pm 10.0$	$326.3 \pm 5.1$	$2.44 \pm 1.86$
232	$57.5 \pm 3.3$	$306.5 \pm 2.6$	$1.36 \pm 0.12$
253	$86.4 \pm 6.0$	$93.1 \pm 7.2$	$2.12 \pm 0.08$
286	$67.7 \pm 13.4$	$226.1 \pm 11.3$	$1.71 \pm 0.34$
345	$56.2 \pm 3.4$	$358.0 \pm 4.2$	$1.12 \pm 0.01$
432	$54.9 \pm 3.7$	$323.5 \pm 3.0$	$1.22 \pm 0.09$
441	$48.4 \pm 4.6$	$216.6 \pm 7.0$	$2.32 \pm 0.19$
488	$130.7 \pm 5.4$	$262.4 \pm 1.1$	$2.59 \pm 0.34$
550	$30.2 \pm 1.6$	$3.9 \pm 17.2$	$0.97 \pm 0.03$
567 <sup>a</sup>	$22.7 \pm 14.5$	$114.0 \pm 20.3$	$1.27 \pm 3.67$
596	$74.1 \pm 6.4$	$18.6 \pm 13.4$	$4.28 \pm 0.53$
683	$88.9 \pm 7.6$	$64.5 \pm 3.5$	$3.19 \pm 0.32$
3131	$96.2 \pm 8.7$	$6.5 \pm 4.8$	$3.20 \pm 0.67$
Inspection of direct images			
4 <sup>b</sup>	$805 \pm 20$	$212 \pm 2$	$2.04 \pm 0.11$
253 <sup>b</sup>	$283 \pm 13$	$359 \pm 2$	$0.63 \pm 0.08$

<sup>a</sup>These companions are at the edge of the range accessible through aperture masking and thus their measurements are associated with large uncertainties;

<sup>b</sup>These companions were already identified in previous *HST* optical images (Robberto et al. 2013).

astrometry and photometry consistent with our results (Robberto et al. 2013). On the other hand, we did not detect the *HST*-detected companions to H97 550 and H97 744. The former companion is  $\approx 6.5$  mag fainter than its primary in the red portion of the visible and thus well below our detection limit in the near-infrared. The latter is about 2.5 mag fainter than the primary in the near-infrared, but our detection limit for that source is  $\Delta K_s \approx 2.5$  mag, so that the non-detection is still consistent with previous knowledge of the system.

The primary driver of this study is the search for closer companions. Our closure phase analysis resulted in the discovery of 13 companions, with separations ranging from 0.023 to 0.151 arcsec and contrast ratios as high as 4.3 mag. The companions to H97 50

and H97 567 are located at the edge of the range of separations probed by aperture masking and their properties are affected by large uncertainties. None the less, we consider them as real companions as they consistently appear when we use different subsets of calibrators to analyse the data sets for these sources. The companion to H97 567 was also confirmed through its detection in two distinct observations. We also note that this latter binary, with a projected separation of about 9 au, is the only disc-bearing system with no near-infrared excess, suggesting that the disc could be circumbinary in nature, with only modest amount of circumstellar material, while still allowing accretion streamers on the central sources.

Confusion between physically bound companions and chance projection of unrelated stars (another cluster member or a fore/background star) has always been a serious concern in multiplicity studies of the ONC. Using the star count computed for the core of the ONC by Köhler et al. (2006) and integrating down to  $K \approx 12.5$ , or 3 mag deeper than our fainter primaries, we conclude that there is a 0.3 per cent probability of chance alignment with an unrelated star within the 0.15 arcsec outer radius of our aperture masking search space for any one target. Over the whole sample, this results in a 10 per cent probability that there is one such pair among the candidate companions we have identified. As could be expected, given the very small angular scale over which we are searching for companions, this is an unlikely event and we therefore assume from now on that all candidate companions are physically associated to their primaries.

All companions detected in this survey are shown in Fig. 5 along with our individual  $5\sigma$  detection limits. Interestingly, we detected no companion with  $\Delta K_s \lesssim 1$  mag. While this could indicate a dearth of nearly equal-mass binaries, it is important to note that the presence of thermal emission from circumstellar discs (present in the majority of the systems targeted here) can significantly alter the near-infrared brightness of young stars. For similar reasons, we refrain from converting the  $K_s$  flux ratio into a mass ratio as uncertainties on the primary masses and contamination from disc emission are large effects that cannot be satisfyingly handled with single-wavelength observations. We do note, however, that several companions have an apparent magnitude that is  $K > 11.3$ , which is the predicted brightness of an unextincted, 1 Myr-old  $0.08 M_\odot$  object at the distance of the ONC based on the evolutionary models of Allard et al. (2012). In particular, the companions to H97 683 and H97 3131 are more than 1 mag fainter than this limit, making them candidate brown dwarf companions. The fact that high line-of-sight extinctions are common in the ONC raises caution, however. Extinctions as high as  $A_V \approx 10$  mag are found in the ONC (Da Rio et al. 2016). We defer further discussion of the mass ratios of the detected systems and of the nature of these apparently extremely faint companions until further photometric and spectroscopic characterization has been obtained.

Finally, we note the presence of two apparent high-order multiple systems in our sample. We found a close companion to the 0.88 arcsec binary H97 550; the ratio of projected separations in the systems is 29, ensuring that it is most likely dynamically stable in the long term. On the other hand, the situation for the H97 253 system is complicated: not only was it already known as both a spectroscopic and visual binary (see Table 1), but our survey discovered a new 0.086 arcsec companion. This companion is highly unlikely to be the same as the spectroscopic companion since the latter is characterized by a relative radial velocity of at least  $10 \text{ km s}^{-1}$ , i.e. with a semimajor axis that is likely smaller than  $\approx 15$  au, or  $\approx 0.025$  arcsec. H97 253 could therefore be a quadruple system. To be stable on the long term, hierarchical systems must have a ratio of semimajor

axes that exceeds  $\approx 3$ , although the exact threshold is dependent on the eccentricity, mass ratio, and relative inclination of the subpairs (Mardling & Aarseth 1999). With a single epoch of observation and without any knowledge of the extent of projection effects, it is currently impossible to assess the long-term stability of this system, however.

### 3.2 Multiplicity properties

We focus our multiplicity survey on the 10–60 au (0.026–0.155 arcsec) projected separation range, which has not been probed in previous surveys of the ONC and where we have near-uniform sensitivity. In this range, we identified 12 companions to 42 targets, for a raw CSF of  $28.6_{-5.9}^{+7.8}$  per cent (68 percentile uncertainties are computed using binomial statistics). A classical issue inherent to multiplicity surveys based on flux-limited samples is the Branch bias that leads to an overrepresentation of faint binaries. Indeed, the brightness of a binary or high-order multiple system can be sufficient for survey inclusion even though no single star in the system exceeds the threshold. From the system  $K$  magnitude and our measured flux ratios, we determined that four systems (H97 253, H97 345, H97 432, and H97 3131) were included as a result of this bias. Discounting these objects, our surveys revealed 8 companions to 38 targets, for a CSF of  $21.1_{-5.1}^{+8.0}$  per cent. We note that because our sample definition also included a maximum brightness, it is possible that some systems with a primary in our  $K_s$  range but with a companion ended up being excluded from the survey in an ‘anti-Branch bias.’ Given the small numbers of ONC targets lying a few tens of a magnitude brighter than our  $K = 7.5$  upper threshold, though, few systems are likely to be affected in this way. The true CSF in the ONC is therefore likely to be only slightly higher than this estimate.

Fig. 5 shows that most of our companions lie above the  $5\sigma$  detection limit for all single stars, and all but one are brighter than the median detection limit. This suggests that the completeness of our survey to companions is high, at least down to  $\Delta K \approx 3$  mag. It is possible that a handful of companions with  $\Delta K \gtrsim 2$  mag and projected separations smaller than 0.04 arcsec could have been missed, as well as faint ( $\Delta K \gtrsim 4$  mag) companions over most separations. However, evaluating the amplitude of this effect requires making assumptions about the distributions of flux ratio and separation as well as their covariance. We feel that the number of companions discovered in our survey is insufficient to enable accurate estimates and chose not to apply a completeness correction. In turn, this means that the companion frequency found in this survey is a conservative lower limit to the actual one.

We fail to identify any significant dependency of stellar multiplicity within our sample. The binary systems possess similar distributions of  $K$  magnitude, spectral type, and estimated primary mass as the observed sample, and their spatial distribution in the cluster is also indistinguishable from that of single stars (see Figs 2, 3, and 4). We conclude that our estimated CSF applies to the ONC as a whole, at least out to 2 pc from  $\theta^1$  Ori C.

At first glance, there appears to be an excess of companions among disc-bearing targets (22 and 28 per cent with and without correction for the Branch bias, respectively) over discless targets (10 per cent). However, the small number of targets in the latter category - there is only one binary in that subsample - leads to large uncertainties and the difference is not statistically significant. None the less, this result is surprising since visual companions with separation smaller than 40–50 au have previously been found to be predominantly associated with disc-free T Tauri stars in other SFRs

(Cieza et al. 2009; Kraus et al. 2012; Cheetham et al. 2015). These past studies, however, considered several nearby SFRs but did not include Orion due to the inability to identify such close companions at this larger distance. This could indicate that disc formation and survival in close binaries proceeds differently in a dense cluster like the ONC compared to other SFRs, or that the disc survival time in close binaries is similar to, or slightly larger than, the age of the ONC cluster. In the latter scenario, discs would need to dissipate quickly beyond that phase in order to match the results derived from other star-forming regions.

### 3.3 Comparison to other surveys

In order to place our results in context, we must now compare the CSF to that observed among field stars and other young stellar populations. Among field solar-type and low-mass stars, the CSF in the 10–60 au range are  $11.7 \pm 1.6$  per cent and  $6.5 \pm 1.6$  per cent, respectively (Raghavan et al. 2010; Ward-Duong et al. 2015). The CSF we found in the ONC is much higher, roughly twice as high as the field solar-type stars, the more appropriate comparison sample given the make-up of our observed sample. However, owing to small number statistics in our survey, the statistical significance of the difference is not definitive: the excesses over solar-type and low-mass stars are significant at the 91.8 and 99.3 per cent confidence levels ( $1.7\sigma$  and  $2.7\sigma$ ), respectively. None the less, this is the first tantalizing evidence for an excess of multiple systems in the ONC over field stars.

The observed CSF in the Taurus, Ophiuchus, Upper Scorpius SFRs, and the  $\beta$ Pic Moving Group (BPMG) over the same separation range are approximately 22, 16, 16.5, and 19 per cent, respectively (Kraus et al. 2008, 2011; Cheetham et al. 2015; Elliott & Bayo 2016). These are approximate rates, as complex object-dependent completeness corrections have been applied in each of these surveys, but the amplitude of these corrections in our separation range is modest and consistently smaller than the statistical uncertainties, which are typically  $\pm 3$ –5 per cent. The CSF we have measured in the ONC is consistent with those observed in other young stellar populations and, if anything, closer to that observed in Taurus, which has the highest CSF in nearby SFRs.

Fig. 6 illustrates the separation distribution observed in the ONC, other young stellar populations, and among field stars. For the ONC, we adopted the results of Reipurth et al. (2007) for separations larger than 60 au as it is the largest survey to date. In most SFRs, the observed distribution of separations is broad, consistent with the lognormal distribution observed among field stars (Raghavan et al. 2010; Ward-Duong et al. 2015). Indeed, such a parametrization has been successfully used in SFRs (e.g. Kraus et al. 2012; Cheetham et al. 2015). In the ONC, on the other hand, we find a sharp decline in the CSF outside of  $\approx 60$  au, although we do not have sufficient statistical strength to tightly constrain this threshold separation. While Taurus and the ONC have undistinguishable CSFs in the 10–60 au range, Taurus has 2.5 times more companions in the 60–150 au range. Furthermore, the sharp decline around 60 au identified in this study contrasts with the rather shallow separation distribution between 60 and 600 au, suggesting that the shape of the separation distribution is intrinsically different in the ONC compared to other SFRs and to the field population.

Finally, since the ONC is a plausible precursor to Pleiades-like clusters, it is meaningful to compare the companion fraction we observe in the ONC to that of nearby open clusters. Bouvier et al. (1997, 2001) and Patience et al. (1998, 2002) probed the visual multiplicity of solar-type stars in the Pleiades, Hyades, Praesepe, and

$\alpha$  Per clusters. While these studies probed separations comparable to those we consider here, their sensitivity to low-mass companions was limited to companions with mass ratios  $\gtrsim 0.3$ –0.4 in this range as a consequence of the older ages of these clusters. These studies applied completeness corrections to alleviate this problem, but this introduces significant uncertainties as the correction factors are large (e.g. a factor of 4 in the 14–50 au range in the Pleiades; Bouvier et al. 1997). Patience et al. (2002) produced a global analysis of all four open clusters, concluding that the frequency of visual companions (26–581 au) in these environments is similar to that of field stars. However, their analysis also showed that the distribution of projected separations is skewed towards tighter separations than in the field, with a peak at  $\approx 4$  au, i.e. a factor  $\approx 10$  tighter than among field stars. This suggests that open clusters are characterized by a relative deficit (alternatively, excess) of companions at hundreds of au (alternatively, tens of au and tighter). The statistical and systematic uncertainties in the derived separation distribution are too large to allow for a definitive comparison with the results of this survey, however.

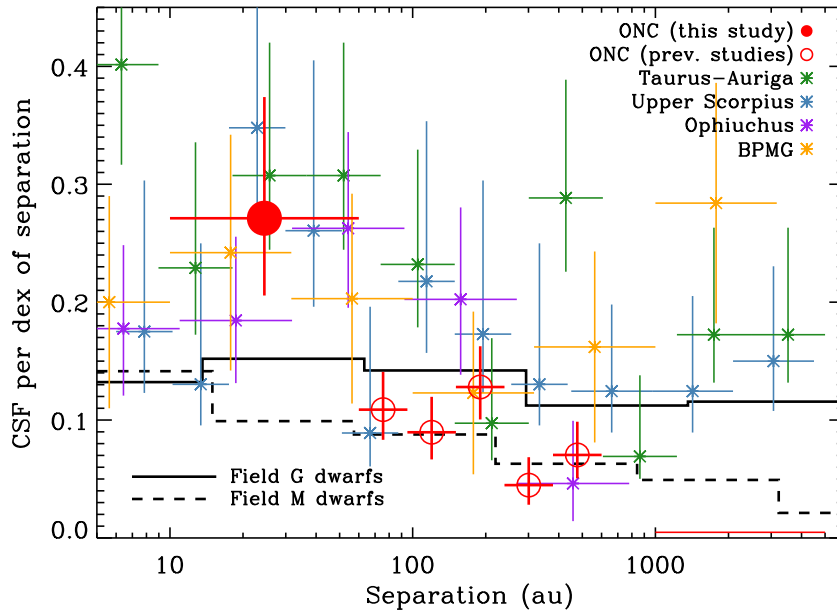
## 4 DISCUSSION

### 4.1 Is the close multiplicity excess in the ONC real?

Taken at face value, our survey has revealed that solar-type members of the ONC host more companions in the 10–60 au range than their field counterparts, the first time such a multiplicity excess is identified in that region. Indeed, the CSF for tight companions in the ONC population is consistent with that observed in other SFRs, contrary to what was found at larger separations over the last two decades. If confirmed, this has profound implications for our understanding of the process through which multiple systems form and to the star formation process at large. Before discussing these implications, it is necessary to evaluate the possibility that the main conclusion of this survey is skewed by uncorrected biases. The most obvious bias associated with multiplicity survey is the Branch bias, which we have corrected for. Hence, more subtle biases must be considered.

First of all, we evaluate whether our observed sample is biased relative to the initial sample from which it was drawn. The spatial distributions of the two samples conform well to one another (see Figs 1 and 2), with the caveat that our survey underrepresents the NE region of the ONC relative to the S and E outskirts of the cluster. Baring a major dynamical anisotropy in the cluster's dynamics, we consider it unlikely that this can significantly affect our analysis. While our sample extends out to 2 pc from the cluster's centre, half of our targets are located within 0.3 pc of the Trapezium (Fig. 1). In other words, our survey primarily focuses on the core of the cluster and we have to consider the possibility that this is a subpopulation with an elevated multiplicity frequency. For instance, mass segregation has been identified in the ONC for high-mass stars (Hillenbrand & Hartmann 1998) and for brown dwarfs (Andersen et al. 2011). While the origin of the former is still debated, the latter is most likely a consequence of the dynamical evolution of the cluster, which expels preferentially its lowest mass members. It is conceivable that this same mechanism preferentially ejects single stars (de La Fuente Marcos 1997), thus leading to a remaining population that has an elevated CSF compared to its initial value. The fact that multiple systems are not more centrally condensed than single stars within our survey suggests that this is not a significant effect. Indeed, we computed the Minimum Spanning Tree (Kruskal 1956) of both the singles and binaries subsamples, and their mean





**Figure 6.** Separation distribution for multiple systems observed among field stars and nearby SFRs. In each bin, the observed CSF is normalized by decade of projected separation to enable direct comparisons between surveys probing different bin sizes. The distribution in the ONC is shown as red circles (this survey as the filled circle and Reipurth et al. 2007) and an upper limit at the widest separations (Scally et al. 1999), whereas the corresponding distributions for the low-mass and solar-type stars in the Taurus-Auriga, Upper Scorpius, Ophiuchus SFRs, and in the BPMG are shown as asterisks (Kraus et al. 2008; Kraus & Hillenbrand 2009; Kraus et al. 2011; Cheetham et al. 2015; Elliott & Bayo 2016). The distributions for G and M dwarfs (continuous histograms) are taken from Raghavan et al. (2010) and Ward-Duung et al. (2015), respectively.

branch lengths are indistinguishable at the  $1\sigma$  level. Furthermore, if a widely dispersed of primarily single stars were now present in the outer regions of the ONC, it would imply that all CSF estimates for that region have so far been overestimated, not just for a specific separation range. The multiplicity survey of Reipurth et al. (2007) covered a very similar area to ours, for instance. Thus, if this were the case, we would conclude that the ONC population has a much lower CSF than the field outside of 60 au, thereby introducing a new mismatch between the ONC and field populations.

Secondly, the observed subsample is not significantly biased in terms of brightness compared to the initial sample (Fig. 3), even after accounting for the four systems that were included because of the Branch bias. Besides, in all likelihood some unobserved members of the initial sample also are unresolved binaries that would not meet the minimum brightness criterion based on the brightness of their primary alone.

One possible bias associated with our survey is related to the presence of circumstellar discs in the majority of the systems targeted in this survey. Based on observations of other star-forming regions, this could potentially introduce a bias towards a lower binary companion (see Section 3.2). Possible issues in assessing the presence of a disc (crowding, contamination from the surrounding nebula) as well as the unknown survival time of discs in close binaries prevent us from evaluating the amplitude of this bias, but we conclude that it can only further strengthen the significance of the multiplicity excess in the ONC compared to field stars.

Finally, while the observed sample has a deficit of stars with  $M_* \gtrsim 1.25 M_\odot$  relative to the initial sample (Fig. 4), this is by design so that we can realistically compare our results to surveys of solar-type stars in other environments. Indeed, surveys in nearby SFRs typically include stars with a range of masses that is broader and extends to lower mass than our survey in the ONC, and thus these should in principle be best compared to a weighted average

of the field solar-type and low-mass stars. However, none of the surveys listed above found strong mass dependences of the CSF for visual binaries, nor do we see a significant one in this survey (see Fig. 4). Thus, the comparison between SFRs remains valid. Either way, the CSF observed in the ONC for 10–60 au is well above that observed in the field for both solar-type and lower mass stars. One conceivable way to ascribe the multiplicity excess we find to an underlying stellar mass bias would be if stellar masses in the ONC have been consistently underestimated by a significant amount, so that a significant fraction of our sample consists of intermediate-mass stars. The latter are thought to host a higher frequency of close visual companions (albeit with large uncertainties in the separation range under consideration here; Rizzuto et al. 2013; De Rosa et al. 2014). This seems difficult to reconcile with the spectral type of the targets in our sample, however, as  $2 M_\odot$  stars are expected to be in the mid-G spectral type range according to most evolutionary models (e.g. Manara et al. 2012). On the basis of the available data, we thus exclude that our sample is strongly affected by intermediate-mass stars.

In summary, no significant bias appears to be skewing the conclusions of our survey, and thus we confirm that (1) solar-type members of the ONC host an elevated CSF – by a factor of almost 2 – in the 10–60 au range compared to field stars, and (2) that the CSF observed in the ONC is fully consistent with that observed in other SFRs. We now turn our attention to the implications of these findings.

#### 4.2 Long-term stability of ONC close binaries

Binaries with semimajor axes of just a few tens of au are stable over billions of years once they are released in the Galactic field (Weinberg, Shapiro & Wasserman 1987). Thus, if the excess of close binaries in the ONC is a temporary feature, whereby some of

these systems will either break apart or significantly change their orbital period, it must be as a consequence of processes internal to the ONC and/or to the multiple system itself. We address both of these possibilities here. To reconcile the observed CSF in the ONC with that of the field, roughly half of the 10–60 au companions range must be removed from that range.

There are numerous indicators that the ONC is a dynamically rich environment. The lack of very wide binaries (Scally et al. 1999) and the apparent deficit of binaries wider than 200 au in the inner pc of the cluster (Reipurth et al. 2007) are likely indicative of dynamically violent interactions affecting multiple systems in the cluster. It is therefore worth exploring whether the close binaries identified in this survey can survive the long-term evolution of the cluster until its dissolution in the field. The dynamical state of the ONC is not firmly established; it may be expanding – in the initial phases of dissolution – or close to virial equilibrium (Allison et al. 2009; Tobin et al. 2009; Da Rio et al. 2017; Kroupa et al. 2018). Either way, the cluster was (much) denser in the past and, as a consequence, most disruptive interactions occurred earlier in its evolution (e.g. Kroupa et al. 1999). As a rule of thumb, a binary system will get destroyed by a passing third body if the relative velocity of the encounter is equal to the orbital velocity of the binary (Hills 1990). Assuming random directions for the travelling directions of systems, the encounter velocity can be approximated as twice the velocity dispersion of the population. Given the current velocity dispersion in the cluster ( $\approx 2 \text{ km s}^{-1}$ ; Da Rio et al. 2017), this implies that systems with orbital velocities of  $\gtrsim 4 \text{ km s}^{-1}$  can survive contemporary and future interactions in the cluster. Assuming a mean system mass of  $1.5 M_{\odot}$  and circular orbits, this orbital velocity corresponds to a semimajor axis of  $\approx 80 \text{ au}$ . Therefore, we conclude that the close binary systems studied here are stable against the future evolution of the ONC.

An alternative mechanism to dynamically alter the close binaries we have identified is related to the evolution of compact three-body systems. If such systems are not hierarchical, i.e. when the ratio of the outer and inner semimajor axes is  $\lesssim 3$ , mutual interactions typically lead to a tightening of the inner pair and a corresponding expansion of the outer orbit, sometimes up to the point of instability and ejection. The time-scale for this evolution depends on the initial separations, and could be on the order of a few Myr for systems similar to those we are probing in the ONC (e.g. Reipurth & Mikkola 2012). Thus, it is possible that some of the binaries we have identified will evolve significantly before the cluster is fully dissolved, crucially displacing the companions to outside the 10–60 au range. We have only identified two high-order multiple systems, but it is plausible that some high-order systems are still unaccounted for. It is unlikely that such missing companions would be located at larger separation, as direct imaging can readily detect any stellar companion to a solar-type ONC member. Therefore, for the ‘unfolding triple system’ scenario to account for the apparent excess of 10–60 au companions, the missing companions must be closer in, at separations of a few au. However, the distribution of separation declines at separations of  $\lesssim 10 \text{ au}$  for both the field population and in SFRs (e.g. Raghavan et al. 2010; Elliott et al. 2015), and the CSF observed among solar-type field stars in the 1–10 au range is only about 12 per cent. It is therefore unlikely that several of the binary systems identified here also possess a closer in third component that could significantly affect the orbit of the detected companion.

In summary, the present and future dynamical states of the ONC, as well as the likely proportion of high-order multiple in our sample, appear insufficient to effectively remove many 10–60 au companion.

Thus, the elevated CSF we have found in the ONC will remain mostly unchanged as the cluster is dissolved into the Galactic field.

### 4.3 Implications

Our survey has revealed that solar-type members of the ONC host twice as many companions in the 10–60 au range as their field counterparts at a high confidence level, the first time such a multiplicity excess is identified in that SFR. Indeed, the CSF for tight companions in the ONC population is consistent with that observed in other SFRs, contrary to what has already been documented at larger separations. Furthermore, the distribution of orbital separation in the ONC is characterized by a sharp drop-off outside of 60 au that is unlike what is seen in other populations, either in SFRs or in the field. We now discuss how these findings affect our understanding of star formation at large.

While the results of this survey cannot definitively solve the ‘nature versus nurture’ debate regarding multiplicity, the fact that all SFRs that have been probed to date shares a similar CSF over the 10–60 au range is more naturally consistent with the hypothesis of a universal set of initial multiplicity properties. Indeed, calculations by Kroupa et al. (2001) and Parker & Goodwin (2012) tailored to reproduce the occurrence of wider binaries in the ONC and based on Taurus-like initial conditions predict a marked excess in the ONC over field stars at separation  $\lesssim 100 \text{ au}$ , in good agreement with our findings. Fundamentally, binaries tighter than 60 au are too hard to be significantly affected by the past evolution of the cluster. Furthermore, the predicted sharp decline with increasing separation out to 1000 au and the absence of even wider systems is fully consistent with all observations of the ONC. While it remains speculative to trace back the population of wider systems in the ONC since it depends on the dynamical history of the cluster, our survey was designed to probe pristine multiple systems, i.e. systems that have not been affected by this prior evolution. Thus, the match in CSF between the ONC and other SFRs indicates that, at least for the 10–60 au separation range, star formation proceeds to a near-universal CSF irrespective of the region.

In turn, this implies that the global properties of a giant molecular cloud play a negligible role in the formation of multiple systems, since the relatively quiescent environment of the Taurus SFR, for instance, is dramatically different from the ONC. Instead, our results suggest that the formation multiple system depends primarily on local conditions, and that these conditions must be sufficiently similar in all SFRs. For instance, this could happen if some self-regulatory process leads to prestellar cores that are comparable in all environments, leading them to fragment in a similar fashion. This is qualitatively consistent with effect of cloud turbulence, whose amplitude and power spectrum only mildly affect the resulting multiplicity properties (Delgado-Donate et al. 2004; Bate 2009). Conversely, the influence of magnetic field and radiative feedback appears more significant, albeit this is still an ongoing debate (e.g. Hennebelle & Teyssier 2008; Price & Bate 2008; Offner et al. 2009; Bate 2012; Lomax et al. 2015). The question of whether and how cloud formation and collapse can self-regulate, thus leading to a universal set of multiplicity properties remains open, and is beyond the scope of our study. We note, however, that observed properties of prestellar cores in isolated situations (e.g. in the Taurus SFR) differ in size, density and level of turbulence from those found in more clustered environments (Ward-Thompson et al. 2007), possibly indicating that the self-regulation process is enacted after the formation of the prestellar cores.

While our findings support a near-universal set of initial multiplicity properties, this renews the question of the origin of field stars. Previous observations of multiple systems in the ONC, on scales of a few hundred au, were consistent with the field and, thus, the idea that the field is primarily populated by stars that have formed in similar, or slightly looser, clusters (e.g. Kroupa 1995; Patience et al. 2002). Our results now exclude this scenario given the observed excess of companions in the 10–60 au range. Indeed, since a wide range of SFRs share the same CSF in this range, if the Galactic field was primarily populated from SFRs like the ONC or less dense ones, there would be twice as many tight companions in the field population as is actually observed. One possible solution to this problem is to assert that most field stars form in yet denser clusters than the ONC, which can effectively destroy even the close visual binaries we probed in this study. This is problematic at two levels, however. First of all, while studies based on cluster counts favour the idea that clusters of a broad range of sizes contribute to star formation in the solar neighbourhood, they are dominated by clusters that are less dense and rich than the ONC, not denser and richer (e.g. Adams & Myers 2001; Bressert et al. 2010; Ward & Kruijssen 2018). The steep power-law slope of the mass distribution of stellar clusters (Adams 2010, and references therein) also refutes the idea that most field stars arise from very rich clusters.

Secondly, such dense clusters have the ability to destroy essentially all binaries wider than 100–200 au, which would introduce a different but equally problematic mismatch with the field population. This issue is actually a profound one. In short, a given initial cluster density results in a final orbital period distribution that is a truncated version of the initial one, with a sharp decline around the ‘destruction limit’ (corresponding to about 60 au in the ONC). While this is consistent with observations of the ONC and of much lower density environments such as Taurus, the field population is characterized by a broad distribution of orbital periods that cannot be reproduced by a linear combination of cluster densities under the assumption of universal initial multiplicity properties. Indeed, the necessity of a large fraction of stars formed in relatively loose environments to account for the rich population of wide binaries in the field would in turn result in a much higher CSF at shorter separation that is inconsistent with the field population.

In summary, the field population of solar-type multiple systems cannot be accounted for by the dynamical evolution of a universal initial population, even if one considers a broad diversity of star-forming environments that spans the range from regions like the Taurus association and the core of the ONC (Ophiuchus and Upper Scorpius are intermediate in richness and density between these two extremes). Multiplicity surveys for similarly close binaries in other Orion subregions, such as the outer ONC, the low-density L1641 cloud, and the NGC 2024, 2068, and 2071 clusters, would be most valuable to test whether the universality holds throughout Orion. Instead, it is possible that field stars form majoritarily in environments that are not well represented by the SFRs located within 500 pc of the Sun and, crucially, that these environments would give birth to a population of multiple systems that is significantly different. In other words, we are led to the paradoxical conclusion that, while nearby SFRs are consistent with a universal output of multiple systems, this does not apply to other environments which must none the less account for a majority of field stars. The notion that nearby SFRs are not representative of star formation on Galactic scales is uncomfortable, given that we rely on these regions to inform our current understanding of star formation. Since solar-type field stars are several Gyr-old on average, it could be that the output of star formation in the past led to a universal-but-different set of multiplicity

properties, possibly as a consequence of the lower metallicity in the clouds that produced these older stars. Since core fragmentation is a consequence of the so-called opacity limit, which marks the phase when a collapsing core becomes optically thick and can no longer effectively cool (Larson 1969; Masunaga & Inutsuka 2000), one expects the metallicity of the initial cloud to be an important physical factor as it sets the amount of dust it contains. Qualitatively, lower metallicity cores should be capable of collapsing further before fragmenting – if at all – thereby producing less binaries on the scales of tens of au, the typical fragmentation scale in present-day clouds. A tentative dependency on total multiplicity with metallicity has been suggested among field stars (e.g. Raghavan et al. 2010), although there is still ambiguity in the interpretation due to complex biases (Duchêne & Kraus 2013). Whether such a metallicity dependence on core fragmentation is at the root of the difference in multiplicity properties between field stars and young stellar populations remains an open question for now.

## 5 CONCLUSIONS

We have conducted a near-infrared survey for close visual binaries among 0.3–2  $M_{\odot}$  members of the ONC using the aperture masking technique on the 8-m VLT telescope. This method allows us to probe for the first time the frequency of companions at separations  $\leq 60$  au in this cluster. Out of 42 targets, we have identified 13 new companions. Previous surveys in the ONC, which focused on wider projected separations, have consistently found that the multiplicity in the cluster is consistent with that of the Galactic field population and roughly half as high as observed in other nearby SFRs. In marked contrast, we find a CSF in the 10–60 au range of  $21_{-5}^{+8}$  per cent, which is consistent with other SFRs and roughly double that observed among field-stars after correcting for the Branch bias. Compared to field stars, this excess is significant at the 92–99 per cent level. We find no clear dependency of multiplicity as a function of stellar properties or location in the ONC. Surprisingly, since our sample is dominated by disc-bearing targets, our results suggest that the disruptive effect of close binaries on disc survival are not as marked in the ONC as in other SFRs, or that these effects have not yet reached their full scale. The match in CSF between the ONC and other SFRs, together with the sharp decline towards larger separations is consistent with the hypothesis of a universal set of multiplicity properties in all SFRs coupled with intracluster dynamical evolution. This would indicate that the fragmentation process that gives rise to visual binaries is largely independent of the global properties of the parent molecular cloud and that the local physical properties are sufficiently self-regulated so as to proceed in similar fashion in dense clusters and quiescent associations. In addition, the results of our survey renew the question of the origin of field stars, as the close binaries we identified in the ONC will not be destroyed during the remainder of the cluster dissolution. Thus, if most stars in the field arise from regions similar to, or less dense than, the ONC, they would host a higher frequency of close visual binaries. This may indicate that nearby SFRs are not representative of the conditions that reigned when the majority of field stars formed, several Gyr ago.

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## REFERENCES

- Adams F. C., 2010, *ARA&A*, 48, 47  
 Adams F. C., Myers P. C., 2001, *ApJ*, 553, 744  
 Allard F., Homeier D., Freytag B., Sharp C. M., 2012, in Reylé C., Charbonnel C., Schultheis M. eds, *Low-Mass Stars and Transition Stars/Brown Dwarfs*, EAS Publ. Ser., EDP Sciences, Les Ulis, France, 57, p. 3  
 Allison R. J. et al., 2009, *ApJ*, 700, L99  
 Andersen M., Meyer M. R., Robberto M., Bergeron L. E., Reid N., 2011, *A&A*, 534, A10  
 Bate M. R., 2009, *MNRAS*, 397, 232  
 Bate M. R., 2012, *MNRAS*, 419, 3115  
 Bouvier J., Rigaut F., Nadeau D., 1997, *A&A*, 323, 139  
 Bouvier J., Duchene G., Mermilliod J. C., Simon T., 2001, *A&A*, 375, 989  
 Bouy H., Alves J., Bertin E., Sarro L. M., Barrado D., 2014, *A&A*, 564, A29  
 Bressert E. et al., 2010, *MNRAS*, 409, L54  
 Cheetham A. C., Kraus A. L., Ireland M. J., Vieza L., Rizzuto A., Tuthill P. G., 2015, *ApJ*, 813, 83  
 Cieza L. A. et al., 2009, *ApJ*, 696, L84  
 Da Rio N., Robberto M., Soderblom D. R., Panagia N., Hillenbrand L. A., Palla F., Stassun K., 2009, *ApJS*, 183, 261  
 Da Rio N., Robberto M., Soderblom D. R., Panagia N., Hillenbrand L. A., Palla F., Stassun K., 2010, *ApJ*, 722, 1092  
 Da Rio N. et al., 2016, *ApJ*, 818, 59  
 Da Rio N. et al., 2017, *ApJ*, 845, 105  
 de La Fuente Marcos R., 1997, *A&A*, 322, 764  
 De Rosa R. J. et al., 2014, *MNRAS*, 437, 1216  
 Delgado-Donate E. J., Clarke C. J., Bate M. R., 2004, *MNRAS*, 347, 759  
 Duchêne G., 1999, *A&A*, 341, 547  
 Duchêne G., Kraus A. L., 2013, *ARA&A*, 51, 269  
 Duchêne G., Bouvier J., Simon T., 1999, *A&A*, 343, 831  
 Elliott P., Bayo A., 2016, *MNRAS*, 459, 4499  
 Elliott P. et al., 2015, *A&A*, 580, A88  
 Fűrész G., Hartmann L. W., Megeath T., Szentgyorgyi A. H., Hamden E. T., 2008, *ApJ*, 676, 1109  
 Goodwin S. P., Whitworth A. P., Ward-Thompson D., 2004, *A&A*, 423, 169  
 Goodwin S. P., Kroupa P., Goodman A., Burkert A., 2007, in Reipurth B., Jewitt D., Keil K. eds, *Protostars & Planets V*, Univ. Arizona Press, Tucson, AZ, p. 133  
 Hennebelle P., Teyssier R., 2008, *A&A*, 477, 25  
 Hillenbrand L. A., 1997, *AJ*, 113, 173  
 Hillenbrand L. A., Strom S. E., Calvet N., Merrill K. M., Gatley I., Makidon R. B., Meyer M. R., Skrutskie M. F., 1998, *AJ*, 116, 1816  
 Hillenbrand L. A., Hartmann L. W., 1998, *ApJ*, 492, 540  
 Hillenbrand L. A., Hoffer A. S., Herczeg G. J., 2013, *AJ*, 146, 85  
 Hills J. G., 1990, *AJ*, 99, 979  
 Kim K. H. et al., 2016, *ApJS*, 226, 8  
 King R. R., Goodwin S. P., Parker R. J., Patience J., 2012, *MNRAS*, 427, 2636  
 Köhler R., Petr-Gozens M. G., McCaughrean M. R., Bouvier J., Duchene G., Quirrenbach A., Zinnecker H., 2006, *A&A*, 485, 461  
 Kounkel M., Megeath S. T., Poteet C. A., Fischer W. J., Hartmann L., 2016, *ApJ*, 821, 52  
 Kounkel M. et al., 2017, *ApJ*, 834, 142  
 Kraus A. L., Hillenbrand L. A., 2009, *ApJ*, 703, 1511  
 Kraus A. L., Ireland M. J., Martinache F., Lloyd J. P., 2008, *ApJ*, 679, 762  
 Kraus A. L., Ireland M. J., Martinache F., Hillenbrand L. A., 2011, *ApJ*, 731, 8  
 Kraus A. L., Ireland M. J., Hillenbrand L. A., Martinache F., 2012, *ApJ*, 745, 19  
 Kroupa P., 1995, *MNRAS*, 277, 1491  
 Kroupa P., Bouvier J., 2003, *MNRAS*, 346, 343  
 Kroupa P., Petr M. G., McCaughrean M. J., 1999, *New Astron.*, 4, 495  
 Kroupa P., Aarseth S., Hurley J., 2001, *MNRAS*, 321, 699  
 Kroupa P., Jerabkova T., Dinnbier F., Beccari G., Yan Z., 2018, *A&A*, 612, A74  
 Kruskal J. B., 1956, *Proc. American Mathematical Society*, 7, 48  
 Lacour S., Tuthill P., Amico P., Ireland M., Ehrenreich D., Huelamo N., Lagrange A.-M., 2011, *A&A*, 532, A72  
 Lada C. J., Muench A. A., Haisch K. E., Jr, Lada E. A., Alves J. F., Tollestrup E. V., Willner S. P., 2000, *AJ*, 120, 3162  
 Larson R. B., 1969, *MNRAS*, 145, 271  
 Lomax O., Whitworth A. P., Hubber D. A., Stamatellos D., Walch S., 2015, *MNRAS*, 447, 1550  
 Manara C. F., Robberto M., Da Rio N., Lodato G., Hillenbrand L. A., Stassun K. G., Soderblom D. R., 2012, *ApJ*, 755, 154  
 Mardling R., Aarseth S., 1999, in Steves B. A., Roy A. E. eds, *The Dynamics of Small Bodies in the Solar Systems*. Kluwer, Dordrecht, p. 385  
 Marks M., Kroupa P., 2011, *MNRAS*, 417, 1702  
 Marks M., Leigh N., Giersz M., Pfalzner S., Pflamm-Altenburg J., Oh S., 2014, *MNRAS*, 441, 3503  
 Masunaga H., Inutsuka S.-i., 2000, *ApJ*, 531, 350  
 Megeath S. T., 2012, *AJ*, 144, 192  
 Moeckel N., Bate M. R., 2010, *MNRAS*, 404, 721  
 Offner S. S. R., Klein R. I., McKee C. F., Krumholz M. R., 2009, *ApJ*, 703, 131  
 Padgett D. L., Strom S. E., Ghez A., 1997, *ApJ*, 477, 705  
 Parker R. J., Goodwin S. P., 2012, *MNRAS*, 424, 272  
 Parker R. J., Goodwin S. P., Kroupa P., Kouwenhoven M. B. N., 2009, *MNRAS*, 397, 1577  
 Parker R. J., Wright N. J., Goodwin S. P., Meyer M. R., 2014, *MNRAS*, 438, 620  
 Patience J., Ghez A. M., Reid I. N., Weinberger A. J., Matthews K., 1998, *AJ*, 115, 1972  
 Patience J., Ghez A. M., Reid I. N., Matthews K., 2002, *AJ*, 123, 1602  
 Petr M. G., Coudé du Foresto V., Beckwith S. V. W., Richichi A., McCaughrean M. J., 1998, *ApJ*, 500, 825  
 Price D. J., Bate M. R., 2008, *MNRAS*, 385, 1820  
 Raghavan D. et al., 2010, *ApJS*, 190, 1  
 Reipurth B., Mikkola S., 2012, *Nature*, 492, 221  
 Reipurth B., Guimaraes M. M., Connelley M. S., Bally J., 2007, *AJ*, 134, 2272  
 Rizzuto A. C. et al., 2013, *MNRAS*, 436, 1694  
 Robberto M. et al., 2013, *ApJS*, 207, 10  
 Scally A., Clarke C., McCaughrean M. J., 1999, *MNRAS*, 306, 253  
 Sicilia-Aguilar A. et al., 2005, *AJ*, 129, 363  
 Siess L., Dufour E., Forestini M., 2000, *A&A*, 358, 593  
 Sterzik M. F., Durisen R. H., Zinnecker H., 2003, *A&A*, 411, 91  
 Szegedi-Elek E., Kun M., Reipurth B., Pál A., Balázs L. G., Willman M., 2013, *ApJS*, 208, 28  
 Tobin J. T., Hartmann L., Fűrész G., Mateo M., Megeath S. T., 2009, *ApJ*, 697, 1103  
 Tuthill P., et al., 2010, in McLean I. S., Ramsay S. K., Takami H., eds, *Ground-based and Airborne Instrumentation for Astronomy III*, Proc. SPIE Conf. Ser., Bellingham, USA, p. 10.  
 Ward J. L., Kruijssen J. M. D., 2018, *MNRAS*, 475, 5659  
 Ward-Duong K. et al., 2015, *MNRAS*, 449, 2618

Ward-Thompson D., Andre P., Crutcher R., Johnstone D., Onishi T., Wilson C., 2007, in Reipurth B., Jewitt D., Keil K., eds, *Protostars & Planets V*. Univ. Arizona Press, Tucson, AZ, p. 33  
Weinberg M. D., Shapiro S. L., Wasserman L., 1987, *ApJ*, 312, 367

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