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The Accretion Discs in Hα with OmegaCAM (ADHOC) Survey

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We present the first results of the Accretion Discs in Hα with OmegaCAM (ADHOC) survey, which aims to perform a deep and homogeneous photometric study of pre-main sequence (PMS) stars in a number of nearby star-forming regions. We took advantage of the exquisite image quality and wide-field capabilities of OmegaCAM at the VLT Survey Telescope (VST) to perform multi-band (*ugri* and Hα), deep (i_{SDSS} < 22 mag), homogeneous and wide-field (covering tens of parsecs) observations of eight star-forming regions: the Orion Nebula Cluster, Lupus, Sco-Cen, Haffner 18, Vela OB2, Eta Cha, Chamaeleon and Ophiuchus. Using a robust method to identify PMS stars through their photometric excess in the Hα band, we aim to measure physical parameters (including mass accretion rates) for over 10 000 PMS stars. Direct comparison with low-resolution spectroscopy confirms that the objects with Hα excess emission that are detected photometrically are bona-fide PMS stars. The first results from this study clearly demonstrate the validity of the observational approach to unveiling complex stellar populations in young clusters.

Discs around young stars

The way in which planets form is intimately connected with the properties of the circumstellar discs in which they are born. In particular, the timescale of disc survival sets an upper limit to the timescale of planet formation, becoming a stringent constraint for planet formation theories. It is generally accepted that nearby protoplanetary discs dissipate in a very short time (2–3 Myr; Fedele et al., 2010). This leaves a very narrow window of opportunity for planets to form. All proposed models of planet formation must predict rapid and very efficient formation of planetary systems within a few million years.

Interestingly, the first studies of PMS stars covering areas spanning tens of parsecs surrounding young stellar clusters in the Magellanic Clouds revealed the existence of a significant number of PMS objects with active circumstellar discs between the ages of 10–50 Myr (for example, De Marchi et al., 2013). Such old PMS accretors are only found sporadically in nearby star-forming regions (for example, Ingleby et al., 2014). However, the evidence is mounting that searches for PMS objects in nearby star-forming regions may be biased towards areas of a few square parsecs around regions of high stellar density. In such regions, disc disruption is driven by environmental effects like rapid disc erosion and dynamical interactions (for example, Vincke & Pfalzner, 2016). These conditions are unlikely to be representative of most star formation. It is therefore imperative to extend the studies of disc populations to include wide regions of diffuse star formation, covering several square parsecs.

In a pilot project (Beccari et al., 2015) we used the Wide Field Imager (WFI) at the MPG/ESO 2.2-metre telescope at the La Silla Observatory to study the population of PMS objects in a region of 15 × 15 arcminutes (corresponding to 17 square parsecs at a distance of 2.9 ± 0.3 kpc) around the young star cluster Trumpler 14 in the Carina Nebula. Using a combination of *V* and *I* broad-band photometry, together with Hα narrow-band images (ESO Programme ID 090.C-0647; Principal Investigator: G. Beccari), we identified PMS stars as Hα-excess emitters with photometrically measured Hα equivalent width EW(Hα) > 20 Å, which is a clear signature of accretion from the disc onto the central star (for example, Calvet et al., 2000).

By comparing the position of PMS objects in the colour-magnitude diagram (CMD) with PMS isochrones, we discovered that, in addition to a well-known young population, Trumpler 14 contains objects older than 10 Myr that are still unambiguously undergoing mass accretion and, therefore, must still have circumstellar discs. Moreover, by studying the cumulative radial distribution of PMS stars with respect to the centre of Tr 14, we demonstrate that PMS stars older than 10 Myr are more spatially dispersed than the young PMS objects in the same field, in agreement with their older ages and velocity dispersions of a few km s^{-1}.

All of these findings clearly question the simple picture in which discs dissipate on their own in less than 3 Myr, and hence challenge the common understanding of protoplanetary disc evolution, possibly implying a new scenario for the mechanism controlling planet formation. It is

Figure 1. True-colour image of the Orion Nebula Cluster obtained using OmegaCAM data, with a 59.95 × 46.56-arcminute field of view.

still an open question why these old accreting PMS stars are not yet systematically observed in nearby low-mass star-forming regions. Thus, we decided to perform a deep search for this population using the VST wide-field camera OmegaCAM.

OmegaCAM observations

We took advantage of the wide-field capabilities (1 square degree) of OmegaCAM to carry out a deep ($i_{SDSS} \leq 22$, corresponding to masses > 0.1 $M_{\odot}$) wide-field study (up to 25 square degrees; > 10pc) of eight star-forming regions in the Galaxy. The observations were distributed over four ESO observing periods for a total of 355 hours using "filler conditions", i.e., exploiting the poorest observing conditions available at the VLT (ESO Programme IDs: 096.C-0730(A), 097.C-0749, 098.C-0850 and 099.C-0474). Most of the regions were observed with the SDSS *ugri* broad-band filters (hereafter referred to simply as *ugri*) and the NB659 (Hα) narrow-band filter. The observations were designed following the same observational strategy adopted by the ESO Public Survey VST Photometric Hα Survey of the Southern Galactic Plane (VPHAS+; Drew et al., 2014): each targeted region was sampled in groups of three overlapping fields, and in each group the fields are contiguous with a footprint close to 3 × 1 square degrees. For each position in the sky we acquired two exposures of 70 seconds in *u* and *g*, two exposures of 25 seconds in *r* and *i* and three images taken with the Hα filter using 150-second exposures.

The entire dataset was fully processed, from the bias, flatfield and linearity correction to the stellar photometry, at the Cambridge Astronomical Survey Unit (CASU). The magnitude for each star was extracted using aperture photometry, adopting an algorithm based on IMCORE[1] and the nightly photometric calibrations were also performed. The astrometrically and photometrically calibrated single-band catalogues are available for download from the VST archive at CASU[2]. Stars lying in the overlap region between adjacent fields were used to adjust residual photometric offsets. The photometric calibration of the final band-merged catalogues was performed against a catalogue of stars from the AAVSO Photometric All Sky Survey (APASS), used as a secondary standard catalogue.

With this new set of observations, we are now able to homogeneously sample the PMS stellar population of each target in an area of tens of square parsecs. As clarified in the previous section, this approach is critical in order to perform an unbiased study of the star formation in nearby regions, and to unveil the properties of the PMS stars showing ongoing accretion in order to eventually establish the existence of old circumstellar discs still feeding the central star. In the following section, we will present surprising and unexpected results obtained for two of the regions that we observed.

The complex stellar population in the Orion Nebula Cluster

The first results of our ADHOC survey were published in Beccari et al. (2017), and illustrated the potential of our proposed approach. In Figure 1 we show a true-colour image of the Orion Nebula Cluster (ONC) derived from OmegaCAM observations. In Figure 2a, we show a zoomed-in portion of a CMD of stars detected within a radius of 1.5 degrees (11.2 parsecs) from the centre of the ONC. The distance of each star from the mean ridgeline of the main population of PMS stars is shown in Figure 2b. Panel c of Figure 2 shows the histogram of the colour (*r* – *i*) displacement, and reveals three distinct PMS populations which are well separated in the colour-magnitude diagram.

There are two possible explanations of this feature: a population of unresolved binaries and triple systems with an exotic distribution of mass ratios; or three different age populations. Independent high-resolution spectroscopy supports the scenario of discrete star formation episodes, separated from each other by about one million years. Thanks to the unprecedented precision of available parallax and proper motion measurements thanks to the publication of the catalogue from Gaia Data Release 2 (Gaia DR2; Gaia Collaboration et al., 2018), we now have an exciting new opportunity to characterise the PMS population in the ONC. In the left panel of Figure 3 we show the colour-magnitude diagram of the entire stellar population sampled within a radius of 1.5 degrees around the ONC; in the right panel of the same figure we show the stellar population selected at the distance of the ONC (~ 400 pc) using parallax. The ONC stellar population is identified with unprecedented accuracy. The data confirm the presence of at least two well-separated populations whose spatial distribution (in α and δ space of parallax) and kinematical properties would be hard to explain if the multiple

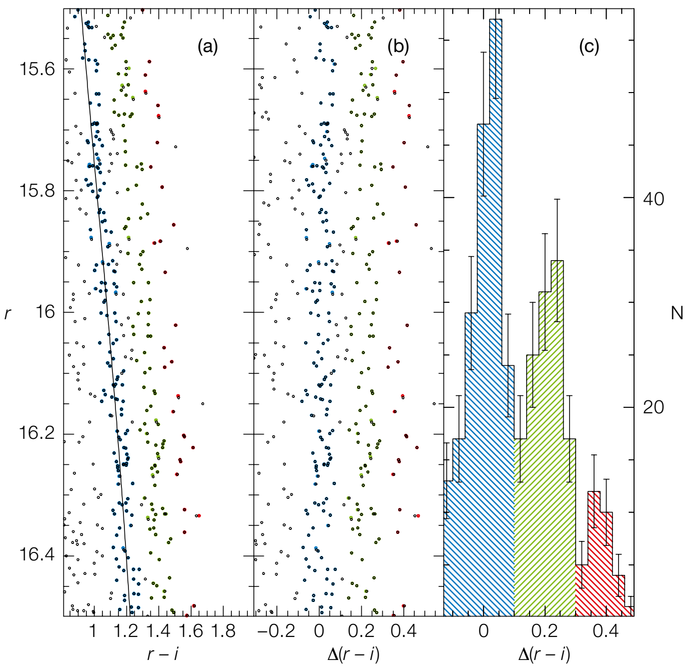
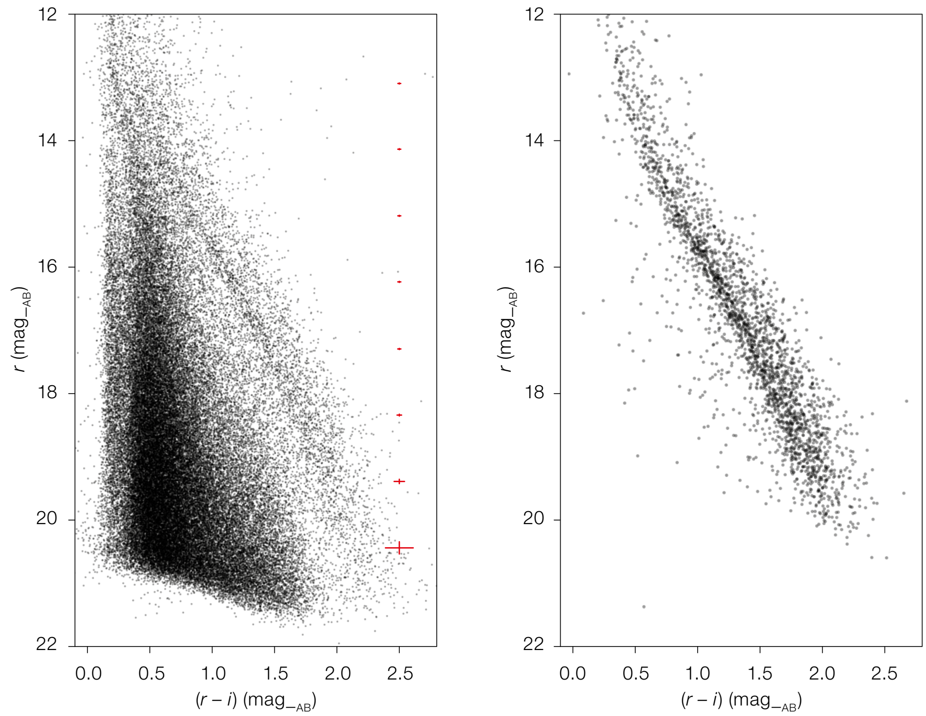


Figure 2. (Left) Colour distribution of the PMS stars in the colour magnitude diagram (CMD) of the central region of the ONC. The black line shows the mean ridge line of the blue population; b) rectification of the CMD shown in panel a); c) histogram of the distance in colour of the PMS stars from the mean ridge line of the bluest population.

Figure 3. (Below) (Left) CMD of the entire stellar population in the ONC area; (right) stars selected using Gaia DR2 parallaxes around the ONC.



sequences in the colour-magnitude diagram were populated solely by multiple systems (Jerabkova et al., 2018).

The Hα filter provides the ability to identify PMS stars that still host gaseous protoplanetary discs from which accretion is still ongoing. Accretion in PMS objects can be identified by searching for excess Hα emission. In Figure 4, we show the dereddened $(r - i)_0$ *vs.* $(r - \mathrm{H}\alpha)_0$ colour-colour diagram of the stars whose membership of the ONC has been verified using Gaia DR2 (grey circles). We use the median $(r - \mathrm{H}\alpha)_{ref}$ de-reddened colours of stars with a small combined photometric uncertainty of less than 0.05 magnitudes in the *r*, *i*, and Hα bands as a function of $r - i$ to define the reference template with respect to which excess Hα emission can be identified (solid line).

We selected a first sample of stars with excess Hα emission by considering all those with $\Delta(\mathrm{H}\alpha) = (r - \mathrm{H}\alpha)_{star} - (r - \mathrm{H}\alpha)_{ref}$ at least four times larger than the photometric uncertainty on the $(r - \mathrm{H}\alpha)_{star}$ colour. Then we calculated the equivalent width of the Hα emission line, EW(Hα), from the measured colour excess using Equation 4 of De Marchi et al. (2010). We finally considered those objects with EW(Hα) > 20 Å (black stars in Figure 4) as bona fide accreting PMS stars. This allows us to safely remove possible contaminants from our sample, such as older stars with chromospheric activity and Ae/Be stars (White & Basri, 2003). Figure 4 shows the spectra of three stars identified as Hα-excess emitters via our photometry (shown as red, blue and black circles on the colour-colour diagram). The spectra were acquired with the ESO Faint Object Spectrograph and Camera 2 (EFOSC2) at the New Technology Telescope during the second ESO/NEON (Network of European Observatories in the North) La Silla Observing School (Selman et al., 2018). The three spectra show a prominent Hα emission line. Despite differences in the values of the spectroscopically measured EW(Hα) (indicated on the side of each spectrum) and the photometrically measured ones (horizontal dashed lines indicate different values of EW(Hα) in the colour-colour diagram) — mostly due to intrinsic Hα variability — this comparison proves the ability of our photometric approach to identify stars with Hα emission (also see Barentsen et al., 2011).

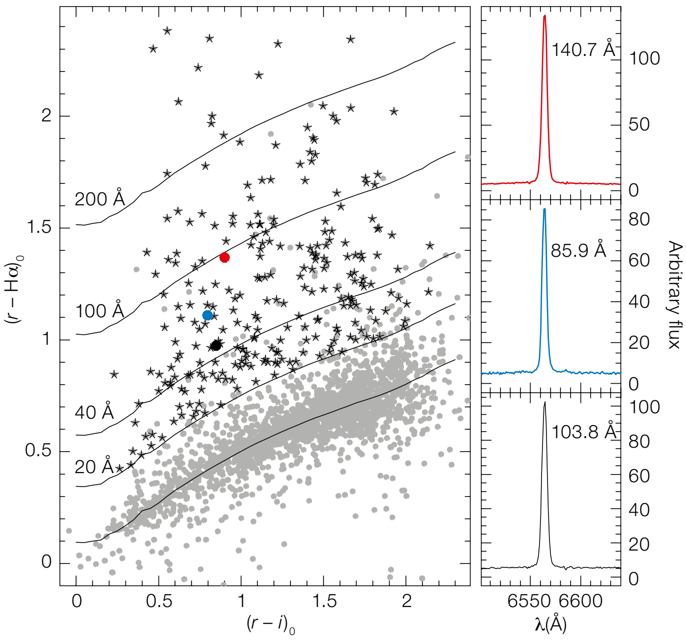


Figure 4. Reddening-corrected colour-colour diagram of the ONC members (grey open circles). The solid line represents the median $(r - \mathrm{H}\alpha)_0$ colour of stars and is defined as the locus of stars without Hα excess emission. The stars with Hα excess emission are shown with black stars. The spectra zoomed on the Hα line for three stars showing Hα in emission are shown on the right.

The Vela OB2 region

Following the successful ONC study, we also investigated the stellar population in the Vela OB2 region. Recently, Jeffries et al. (2014), using radial velocity measurements from the Gaia-ESO Survey (GES; Gilmore et al., 2012), found that the ~ 10 Myr cluster of stars around the Wolf-Rayet star γ^2 Vel (known as the γ Vel cluster) is in fact composed of two coeval but kinematically distinct populations, A and B. Notably, Sacco et al. (2015) performed a similar study of the stellar population around NGC 2547; a ~ 35 Myr star cluster located two degrees to the south of γ Vel. Using the radial velocity distribution of the sampled stars they could identify the main cluster together with a kinematically distinct population whose radial velocity distribution closely resembles the population B discovered in γ Vel.

Together, these results imply that the stars observed by Jeffries et al. (2014) in γ Vel B and Sacco et al. (2015) in NGC 2547 B belong to the same young, low-mass stellar population spread over at least several square degrees in the Vela OB2 complex. In order to investigate the stellar population of the region, we used a 12 × 5 square degree photometric catalogue in the *r*, *i* and Hα filters (obtained as part of the ADHOC survey), combined these with accurate radial velocities from GES, and astrometric information available from Gaia DR2. We first selected the stars in parallax, in the range $2.2 < \varpi < 3.9$ milliarcseconds; i.e., around the location of γ^2 Vel. We only considered stars that have a relative parallax uncertainty smaller than 10%. We then applied the data-clustering algorithm, Density-Based Spatial Clustering of Applications with Noise (DBSCAN; Ester et al., 1996), in order to simultaneously identify clusters in right ascension (α) and declination (δ), and in proper motions μ_α and μ_δ. The result is shown in Figure 5 and is, once again, surprising — revealing six clusters in the region! Two of the clusters were known — γ Vel and NGC 2547 (marked as Cl4 and Cl3, respectively in Figure 5) — while the other four clusters were previously unknown. Using accurate OmegaCAM photometry and the precise parallaxes from the Gaia DR2 catalogue, we conclude that the stellar "B" populations originally discovered in γ Vel and NGC 2547 (Jeffries et al., 2014; Sacco et al., 2015) actually belong to a complex set of clusters, well separated into two coeval groups of 10 and 30 Myr respectively, and overlapping in space over an area of almost 100 square parsecs.

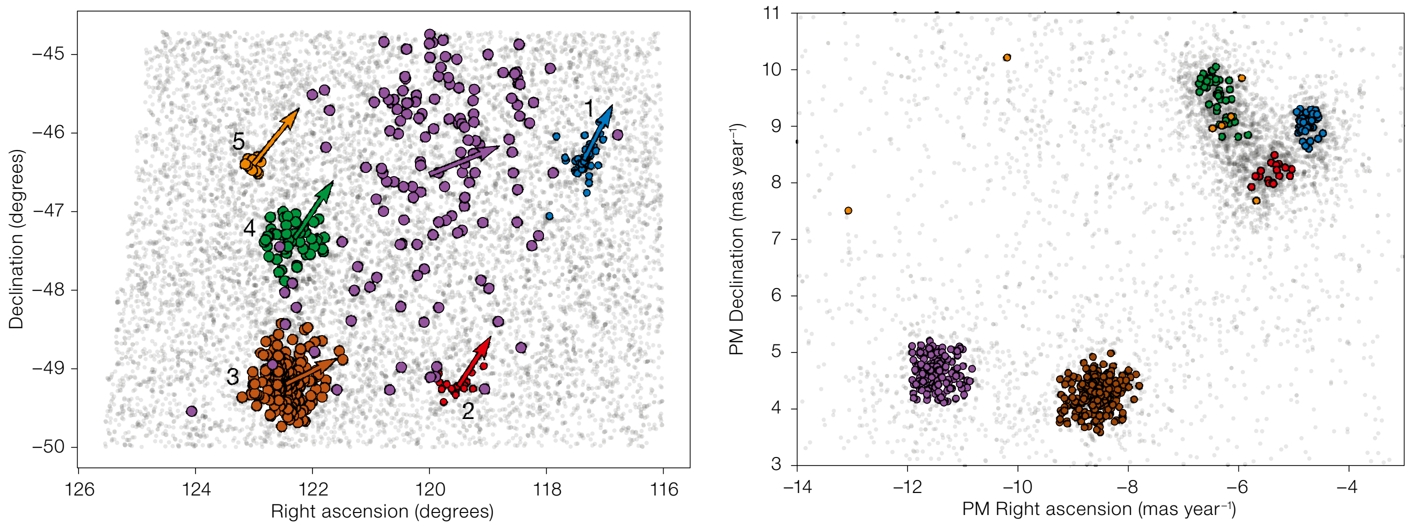


Figure 5. (Above left) identification of clusters in right ascension and declination. Cluster 1 is shown in blue, 2 in red, 3 in brown, 4 in green, 5 in orange and 6 in violet. (Above right) identification of clusters in proper-motion space.

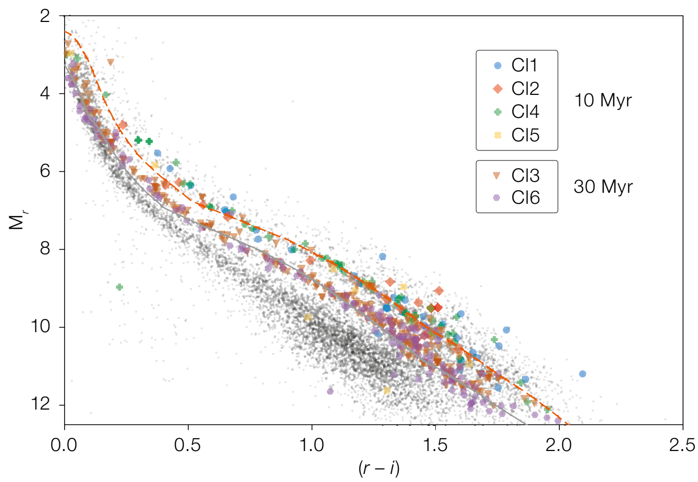


Figure 6. (Left) The colour-magnitude $(r - i) - M_r$ diagram for all stars in the OB2 Vela complex with $2.2 < v < 3.9$ and $\sigma v/v < 0.1$ (black dots) together with the stars of the clusters.

Conclusions

The first results obtained using the ADHOC data clearly demonstrate the importance of wide-field multiband homogeneous data sets covering tens of parsecs, in order to unveil the hidden secrets of the complex stellar populations in young star clusters. While the ADHOC survey offers the opportunity to identify PMS stars through the Hα filter, it is clear that the availability of accurate astrometric data from Gaia DR2 can be efficiently combined to disentangle the stellar populations in 3D. Hence, the primary goal of the ADHOC survey remains the identification of candidate long-lived accreting discs in nearby star-forming regions, which implies that planet formation could proceed on much longer timescales than previously thought. At the same time, we have also proved that the use of wide-field facilities is critical to unveiling the existence of multiple events of star formation in massive and extended star-forming regions. Establishing whether age spreads in the PMS population of clusters are common will have profound implications for theories of star cluster formation, for the meaning and determination of the initial mass function, and for the general assumption that clusters are simple stellar populations.

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Links

[1] Software publicly available at CASU: http://casu.ast.cam.ac.uk
[2] VST archive at CASU: http://casu.ast.cam.ac.uk/vstsp/
[3] Gaia Data Processing and Analysis Consortium: https://www.cosmos.esa.int/web/gaia/dpac/consortium)