The young star population of L1188

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ABSTRACT

We present new results on the young star population of the Lynds 1188 molecular cloud, associated with the Cepheus Bubble, a giant interstellar shell around the association Cep OB2. In order to reveal the star-forming scenario of the molecular cloud located on the supershell, and understand the history of star formation in the region, we identified and characterized young star candidates based on an Hα emission survey and various published photometric datasets. Using Gaia DR2 astrometry we studied the spatial distribution of the young star candidates and isolated three groups based on their distances. We constructed spectral energy distributions of our target stars, based on Pan-STARRS, 2MASS, Spitzer and WISE photometric data, estimating their spectral types, extinctions, and luminosities. We estimated masses by means of pre-main-sequence evolutionary models, and derived accretion rates from the equivalent width of the Hα line. We studied the structure of the cloud by constructing a new extinction map, based on Pan-STARRS data. Our results show that the distribution of low-mass young stars in L1188 is well correlated with that of the dust and molecular gas. We identified two small, compact clusters and a loose aggregate of young stars. We found that star formation in L1188 started about 5 million years ago. The apparent age gradient of young stars across the cloud and the ammonia cores located to the east of the optically visible young stellar groups support the scenario of star formation propagating away from the centre of the Cepheus Bubble.

Key words: Stars: pre-main-sequence – Stars: formation – stars: variables: T Tauri, Herbig Ae/Be – ISM: clouds – ISM: individual objects: Lynds 1188

1 INTRODUCTION

Massive stars affect their environment during their lifetime by ionizing radiation, stellar winds, and at the end of their lives by supernova explosions. During these energetic processes fast-moving shock waves move into the surrounding interstellar medium, creating a giant bubble, filled with hot and tenuous gas, and bordered by the ambient interstellar clouds, interacting with the expanding shock wave. The compression from the shock wave may trigger formation of new stars in the clouds of the bubble shells on timescales of a few tens of million years (Krebs & Hillebrandt 1983). Giant ring-like structures are common in the cold interstellar matter of our Galaxy (e.g. Kiss et al. 2004; Ehlerová & Palouš 2013; Simpson et al. 2012), indicating long-term effects of high-mass stars on their large-scale environments. Propagation of star formation due to expanding bubbles have been observed in several nearby OB associations (e.g. Preibisch & Zinnecker 1999; Bally 2008).

The Cepheus Bubble (Kun et al. 1987) is a ring-shaped infrared emission region with a diameter of 10° around the Cep OB2 association, at a distance of 800–900 pc from the Sun (Ábrahám et al. 2000). CO observations by Patel et al. (1998) revealed some 10⁵ M⊙ molecular gas on the periphery of the Cepheus Bubble. They proposed that a supernova exploded some 1.7 million years ago in the Strömgren sphere–stellar-wind cavity of the oldest sub-system of Cep OB2. Whereas the currently observed OB stars of the association (e.g. the exciting stars of IC1396, Sicilia-Aguilar et al. 2005) might have been born in clouds swept up by the expanding ionization front, the explosion of a high-mass star initiated the birth of the third generation of stars of Cep OB2 in the molecular clouds of the bubble shell.

Lynds 1188 (L1188) is one of the star-forming molecular clouds on the periphery of the Cepheus Bubble, at (l,b)≈(105.6°, 4.2°). Two red and nebulous objects, RNO 140 and RNO 141 (Cohen 1980), a reflection nebula, DG 180 (Dorschner & Gürtl 1963), as well as six IRAS sources with protostellar colour indices (Ábrahám et al.
are associated with L1188. These objects indicate recent star formation in the direction of the cloud.

The $^{13}$CO observations of L1188 by Ábrahám et al. (1995) revealed a total mass of some 1800 $M_\odot$, distributed in six $^{13}$CO clumps. They discovered a dust filament stretching from S140/L1204 toward the L1188 on the 100-$\mu$m optical depth map constructed using IRAS data, indicating that both regions are physically connected. Furthermore they identified fifteen H$\alpha$ emission objects. Three dense NH$_3$ cores were identified in L1188 through an NH$_3$ survey presented by Verebelyi et al. (2013). These ammonia cores are encompassed by three known $^{13}$CO clumps.

Stolovy et al. (2006) selected 73 potential young stellar objects (YSOs) in the mid-infrared images of the L1188 region, obtained by the Spitzer Space Telescope (Werner et al. 2004) during the Spitzer Galactic First Look Survey (http://ssc.spitzer.caltech.edu/fls/galac/). They identified three groups of potential YSOs, and proposed that two of them belong to L1188, whereas the third one is probably a distant star-forming region related to the Perseus spiral arm.

Based on new $^{12}$CO, $^{13}$CO and C$^{18}$O observations, Gong et al. (2017) revealed that L1188 consists of two nearly orthogonal filamentary molecular clouds at two clearly separated velocities. Gong et al. (2017) found enhanced star formation activity in the intersection region, and proposed that star formation is triggered by the collision of molecular clouds in L1188.

To identify and characterize the young star population of L1188, we performed a new H$\alpha$ survey to detect stars showing H$\alpha$ in emission. The earlier objective prism photographic plates were less sensitive (Ábrahám et al. 1995). To examine spectral energy distributions (SEDs), we utilized available photometric data in the Pan-STARRS (Chambers et al. 2016) and IPHAS databases (Barentsen et al. 2014), as well as 2MASS (Cutri et al. 2003), Spitzer (Werner et al. 2004) and WISE (Cutri & et al. 2013). We selected further candidate YSOs based on 2MASS, WISE, and Spitzer colour indices. The Gaia DR2 data allowed us to distinguish members of the L1188 population from foreground and background YSOs. Our data reduction and target selection are described in Section 2. The applied methods are given in Section 3. The results and their discussions are presented in Section 4. A brief summary is given in Section 5.

2 OBSERVATIONS, DATA REDUCTION AND YSO SELECTION

2.1 Observations

We observed L1188 with the Wide Field Grism Spectrograph 2 (WFGS2), installed on the University of Hawaii 2.2 m telescope, on 2012 July 27 and 29, and August 10 and 11. We used a 300 line mm$^{-1}$ grism, blazed at 6500 Å and providing a dispersion of 3.8 Å pixel$^{-1}$ and a resolving power of 820. The narrow band H$\alpha$ filter had a 500 Å passband, centered near 6515 Å. The detector for WFGS2 was a Tektronix 2048×2048 CCD, whose pixel size of 24 $\mu$m corresponded to 0.34 arcsec on the sky. The field of view was 11.5$'$ × 11.5$'$. We covered an area of 60×50 arcmin, centered on R.A.(2000) = 22$^h$ 18$''$ and Dec(2000) = 61° 42', with a mosaic of 30 overlapping fields. During the grism observation we took a short, 60 s exposure for each field in order to identify the H$\alpha$ line in the spectra of bright stars, and avoid saturation. Then we obtained three frames with 300 s exposure time. Direct images with the same instrument were obtained through $r'$ and $i'$ filters before the spectroscopic exposures. One exposure was taken in each filter with integration time of 60 s.

Bias subtraction and flat-field correction of the images were done in IRAF. Then we used the FITS toolkit, a software package for astronomical image processing (Pál 2012), to remove cosmic rays, coadd long-exposure images, identify the stars on the images, and transform the pixel coordinates into equatorial coordinate system and determine equivalent width of H$\alpha$.

We examined the co-added image obtained with the slitless spectrograph visually to discover new young stars showing the H$\alpha$ line in emission. We identified 76 stars with H$\alpha$ emission in the observed region. We determined their equatorial coordinates by matching our images with a 2MASS (Cutri et al. 2003) image of the fields. All H$\alpha$ emission sources have 2MASS counterparts unambiguously within 1.4$''$, thus we use 2MASS designations of the stars for equatorial coordinates. The equivalent width of the H$\alpha$ emission line and its uncertainty were computed in the same way described by Szegedi-Elek et al. (2013). Due to the faint continuum or overlapping spectra we could measure EW(H$\alpha$) only in 26 cases. We could recover 13 of the 18 sources, listed in the IPHAS catalogue of H$\alpha$ emission-line sources (Witham et al. 2008) for the same area.

2.1.1 Photometric data

To find candidate YSOs and then study the evolutionary stage of the selected candidate YSOs we supplemented our data with photometric data available in public databases.

The 2MASS survey (Skrutskie et al. 2006) uniformly scanned the entire sky in three near-infrared bands $J$, $H$, $K_S$ to detect and characterize point sources brighter than about 1 mJy in each band, with signal-to-noise ratio greater than 10, using a pixel size of 2.0$''$.

NASA’s Wide-field Infrared Survey Explorer (WISE, Wright et al. 2010) mapped the whole sky at 3.4, 4.6, 12, and 22 $\mu$m (W1, W2, W3, W4) in 2010 with an angular resolution of 6.1$''$, 6.4$''$, 6.5$''$, and 12.0$''$ in the four bands. WISE achieved 5σ point source sensitivities better than 0.08, 0.11, 1 and 6 mJy in unconfused regions in the four bands.

The Isaac Newton Telescope (INT) Photometric H$\alpha$ Survey of the Northern Galactic Plane (IPHAS) (Barentsen et al. 2014) observed the Northern Milky Way in visible light (H$\alpha$, $r'$, $i'$) down to >20th magnitude, using the INT in La Palma.

A small stripe of our target field (see Fig. 3) was also observed by the Spitzer Space Telescope (Werner et al. 2004) as part of the Spitzer First Look Survey (http://ssc.spitzer.caltech.edu/fls/galac/). The original goals of this survey were to characterize the cirrus and background source counts at low Galactic latitudes and the internal cirrus and background source counts toward a molecular cloud. Observations were performed on 2003 December 6 with the Infrared Array Camera (Fazio et al. 2004) at 3.6, 4.5, 5.8 and 8 $\mu$m and on 2003 December 8 at 24 and
70 µm with the Multiband Imaging Photometer (Rieke et al. 2004) (aors 4959744 and 4961536).

AKARI was a satellite (Murakami et al. 2007) dedicated for infrared astronomical observations. It was capable of observing across the 2-180 µm near-infrared to far-infrared spectral regions, with two focal-plane instruments: the InfraRed Camera (IRC) (Onaka et al. 2007) and the Far Infrared Surveyor (FIS) (Kawada et al. 2007).

The Midcourse Space Experiment (MSX) (Price et al. 2001) surveyed the entire Galactic plane within [b] > 5° in four mid-infrared spectral bands between 6 and 25 µm at a spatial resolution of ~18′′.

2.2 YSO selection

Young stellar objects, bearing a circumstellar disc or embedded in a protostellar envelope, are located at specific regions in near- and mid-infrared colour-colour diagrams. Colour–colour diagrams can be used for identifying embedded protostars (Class I infrared sources) and classical T Tauri stars (Class II sources), defined primarily on the basis of spectral slopes over the 2-24 µm wavelength interval (Lada 1991; Greene et al. 1994). The strong Hα emission of T Tauri stars originates from the interaction of the star and its accretion disc. To characterize the circumstellar environment of our Hα emission stars, and find further candidate YSOs in the region we examined the infrared sources in the Spitzer, WISE, and 2MASS data bases.

2.2.1 Spitzer

We examined all sources within the field of view of our WFGS2 measurements to search for additional young stars. We downloaded Spitzer magnitudes from the Spitzer Enhanced Imaging Products (SEIP) Source List.

Gutermuth et al. (2009) described a classification scheme to distinguish YSOs based on Spitzer colour indices. In the selection method, one performs straight cuts in colour–colour and colour–magnitude diagrams. During this method contaminants (PAH, AGN, shock, more evolved field stars ...) can be eliminated in multiple phases and Class I and Class II sources can be separated.

We applied the methods described by Gutermuth et al. (2009) to remove probable extragalactic, stellar, and interstellar contaminants and select candidate YSOs based on colour indices. We identified 32 Class II and 5 Class I sources, detected in all of the IRAC bands.

We combined the 2MASS magnitudes with the Spitzer [3.6] and [4.5] magnitudes (Fig. 1) and applied also the Phase 2 criteria established by Gutermuth et al. (2009). To exclude the dim extragalactic contaminations we used a [3.6] and [4.5] < 14 magnitude limit. With this method, we recovered 32 additional candidate T Tauri stars.

In the last step, we added [24] mag to the examination as mentioned by Gutermuth et al. (2009) in Phase 3 method. With this step, we found 13 additional young stars. In total, we added 35 new young star candidates to our list. We note that the high-sensitivity Spitzer observations cover less than one-third of the area observed by the WFGS2. Most of our Hα emission stars are located outside the Spitzer field of view, thus probably a large number of faint protostellar and pre-main-sequence members of L1188 are still undetected.

Table 1. Spitzer 70 µm photometry

| Name                  | 70 µm (mJy) |
|-----------------------|-------------|
| SSTSL2 J221521.04+614827.3 | 423.0 ± 31.2 |
| SSTSL2 J221619.80+612620.6 | 321.5 ± 46.8 |
| SSTSL2 J221653.13+614315.5 | 208.6 ± 37.8 |
| SSTSL2 J221702.70+611503.6 | 205.9 ± 33.7 |
| SSTSL2 J221722.25+614305.6 | 1037.2 ± 119.6 |

At 70 µm photometry for the selected sources was carried out on the pipeline processed (post-BCD) filtered images that were downloaded from the Spitzer Heritage Archive. In total, 64 sources of all the young star candidates were situated in the field of view of Spitzer. We detected point-like sources with a level of >4σ at five out of our 64 targeted positions. In the case of SSTSL2 J221653.13+614315.5 and SSTSL2 J221722.25+614305.6, where the detected sources are blended by nearby bright objects, we used PSF photometry to derive the 70 µm flux densities. For the other three targets as well as for the undetected sources we performed aperture photometry using an aperture radius of 8′′ and a background annulus between 39′′ and 65′′. For the detected sources the derived centroid was used as the center of the aperture, while for non-detections the positions of the 2MASS or WISE counterparts were utilized as target coordinates. To account for the flux outside the aperture we applied aperture correction using a correction factor appropriate for a 60 K blackbody. The final uncertainty of the photometry was derived as the quadratic sum of the measurement error and the absolute calibration uncertainty, (7%, MIPS Instrument Handbook). For the undetected targets 3σ upper limits were computed. For two targets (SSTSL2 J221643.39+612417.5 and SSTSL2 J221709.59+611411.5), which are associated with extended emission, no photometry was derived. The results of the 70 µm photometry are listed in Table 1.

2.2.2 WISE

Marton et al. (2016) conducted a comprehensive all-sky search for candidate YSOs in the AllWISE data release applying the Support Vector Machine method. Forty-eight sources of their candidate YSOs (Marton et al. 2016) can be found in our studied region. Twenty-seven of them coincide with sources classified as YSOs during the previous steps, thus twenty-one sources are new young star candidates.

2.2.3 2MASS

We used the 2MASS All-Sky Catalog (Skrutskie et al. 2006) to identify classical T Tauri stars in the observed region. Figure 2 shows the (J−H) vs. (H−Ks) colour-colour diagram for all 2MASS young star candidates in the studied region. The solid curve shows the colours of the zero-age main sequence, and the dotted line represents the giant branch (Bessell & Brett 1988). The long-dashed lines delimit the area occupied by the reddened normal stars (Cardelli, Clayton & Mathis 1989). The dash-dotted line is the locus of unreddened T Tauri stars (Meyer et al. 1997).
and the gray shaded band borders the area of the reddened $K_s$-excess stars. YSO candidates in this diagram are sources having photometric quality flags A or B and whose error bars are entirely in the grey region. Four sources show unusually high infrared excess, so we examined these sources individually (namely 2MASS J22161983+6126204, 2MASS J22182711+6141567, 2MASS J22182711+6141567 and 2MASS J22182711+6141567 (Chen & Yang 2012; Alksnis et al. 2001), and 2MASS J22161983+6126204 (Hv12) are known carbon stars so we rejected them from the YSO candidate list. Taking into account also the overlapping among the methods we got three new young star candidates in total.

2.2.4 Gaia DR2

Bailer-Jones et al. (2018) derived distances for 1.3 billion stars of Gaia DR2 (Gaia Collaboration et al. 2016, 2018) using a weak distance prior that varies smoothly as a function of Galactic longitude and latitude. We adopted distances for the young star candidates from Bailer-Jones et al. (2018). Based on these data the sources can be divided into three main groups: there is a small foreground population of 9 young stars, 45 sources are much farther than the published distance of L1188, and 66 stars are in the published distance of L1188. No distance is available for 15 stars, so we did not include them directly in the young star candidate list. The average distance of the stars associated with L1188 is $855_{-180}^{+205}$ pc.
Figure 3. Candidate young stars identified during the present survey, overplotted on the DSS2 red image. Blue triangles represent Hα emission stars, while black diamonds indicate candidate PMS stars exhibiting excess emission in the infrared regime. The area bordered by the dashed squares was the target of our Hα survey, while the solid green rectangular indicates the boundary of the region studied by the Spitzer.

served area suggests a possible more widely spread young star population.

3 ANALYSIS

3.1 Spectral Energy Distribution

The available photometric data allowed us to construct the spectral energy distributions (SEDs) of all selected candidate young stars over the 0.36–24 (70) μm wavelength region.

We estimated the spectral type and the extinction of each selected young star, which had measured magnitudes with error in each Pan-STARRS band (u,g,r,i,z) and the 2MASS J magnitude had at least B quality. We applied a reduced χ² method,

\[ \chi^2 = \sum_j \frac{(F_{\text{observed}} - F_{\text{model}})^2}{\sigma^2}, \]

comparing the optical-near infrared SED (from the B to the J-band) with those of a grid of reddened photospheres, using the reddening-free colour indices of Pecaut & Mamajek (2013) \((F_{\text{model}})\), the extinction law of Cardelli et al. (1989), and the \(A_v\) > 1 mag restriction (Gong et al. 2017). We disregarded the effect of veiling because Muzerolle et al. (1998) [see their Fig. 4] have shown that stars with low accretion-rate (see 4.2.2) show very low veiling values. To compare Pan-STARRS colour indices with reddening-free colour indices of Pecaut & Mamajek (2013), we transformed Pan-STARRS magnitudes \((u,g,r,i,z)\) into the Johnson/Cousins system \((B,V,R_c, I_c)\) using the transformation equations presented by Tonry et al. (2012).

We found the best fit of the photometry and photospheric colours using the reddening law \(R_V = 3.1\) for \(A_V < 2.0\), and \(R_V = 5.5\) for \(A_V > 2.0\). The estimated spectral types are ranging from F1 to M2. The most common spectral type is K4. We estimate the accuracy of the resulting spectral type and extinction as ±2 subclass and ±0.5 mag, respectively.

3.2 Extinction mapping

The high sensitivity Pan-STARRS data allow us to refine the picture of the dust column density structure of L1188, compared to available extinction maps of the region (Rowles & Froebrich 2009; Dobashi 2011). We constructed an extinction map, applying the classical method of star counts (Dickman 1978) on the Pan-STARRS data set. We counted the stars within of 60-arcsec radii, whose centres were distributed on a regular grid with step of 30′′. The number of stars with \(V \lesssim 25\) mag within a 1 square degree area was 55709. We removed each star with \(V \lesssim 14\) mag as probable foreground object. The off-cloud reference area was an 1′ × 1′ field centered at RA(2000) =333.67° D(2000) =62.35°, containing 86 stars. The uncertainty of the extinction of a pixel, derived by the formula given in Dickman (1978) and depending on the pixel value itself, extends from \(\sim 0.2\) mag in the low extinction areas (between 0 – 1mag) to 1.1 mag near the extinction peaks. The resulting \(A_v\) map can be seen in Fig. 4.

3.3 Colour-magnitude diagram

We plotted the \(r'\) vs. \(r' - i'\) colour-magnitude diagram using the IPHAS photometry for the candidate young stars, which have the signal to noise ratio >10 in all bands and the object looks like a single, unconfused point source. \(r'\) magnitudes may be affected by the presence of the Hα emission line within the \(r'\) band (Drew et al. 2005; Barentsen et al. 2011). We applied the correction to the \(r'\) magnitudes following Barentsen et al. (2011) and plotted the \(r'\) vs. \(r' - i'\) colour-magnitude diagram of the candidate YSOs in Fig. 5.

We compared the distribution of the sources with semi-empirical PMS isochrones presented by Bell et al. (2014) for the IPHAS bands, based on the Pisa PMS tracks and isochrones (Tognelli et al. 2011) and BT-Settl (Baraffe et al. 2015, and references therein) atmosphere models.

We shifted the model tracks and isochrones according to the average distance of 555 pc, but we did not correct them for the extinction. Instead we corrected individually all of the stars for the extinction with the previously determined individual values using the relationships \(A_v=0.843 A_V\) and \(A_V=0.639 A_V\) by Schlegel et al. (1998).

Most of the YSO candidates in this diagram are scattered between the 10^5 yr and 10^7 yr isochrones plotted for the average distance.

Based on Fig. 5 a few of the YSO candidates are seen to fall near or below the 100 Myr isochrone. Taking into account that extinction can be underestimated, the positions of these stars could move towards slightly younger isochrones.
4 RESULTS AND DISCUSSION

4.1 Cloud Structure

The new extinction map of L1188 can be seen in Fig. 4. To compare the distribution of gas and dust, $^{13}$CO contours (Ábrahám et al. 1995), NH$_3$ cores (Verebélyi et al. 2013), distribution of the young stellar objects, and Planck Galactic cold cores (PGCCs, Planck Collaboration 2015) are overplotted on the extinction map. Class I sources with unknown distances are also overplotted with smaller red downward triangles. Their positions suggest physical connection to L1188. A slight difference can be seen between the $^{13}$CO contours.
1.0

... having detection (...).

... The high-(...).

... The extinction exceeds this (...).

... 2.5

... Dobashi (42×96) responding to a hydrogen column density of 3.03 \times 10^{22} \text{cm}^{-2} (Gaia 2005). They classified two of them as T Tauri stars, and another one as an M3Ve (J22142723+6129433). This star shows strong Hα emission, which can not be explained as chromospheric activity, so we propose it as a YSO candidate.

... We could measure EW(Hα) only in 17 cases. To compare these results with another method, we estimated the EW(Hα) based on the IPHAS r′–Hα vs. r′–i′ colour-colour diagram (Barentsen et al. 2011) for stars, having detection with S/N >10 in each band. The comparison explored no systematic difference between the equivalent widths measured by different methods. Most of the measured equivalent widths are between 10 and 100 \AA, typical of classical T Tauri stars (e.g. Reipurth et al. 1996). The highest values (> 100 \AA) belong to J22174025+6147025 and J22190442+6136250.

Figure 6 shows the IPHAS colour-colour diagram for the candidate young stars detected in each IPHAS band. Blue triangles show Hα emission sources, while black diamonds are infrared excess stars. Synthetic colours of main sequence stars and Hα emission objects are taken from table A1 in Barentsen et al. (2011). The thick red solid line indicates the normal main sequence, and thin solid lines show the main sequence colours modified by Hα emission. Each colour of Hα emission objects and infrared excess stars were dereddened by AV determined during the analysis. It can be seen that not all of the candidate YSOs appear as Hα emission stars in this diagram. Five of the infrared excess stars seem to be also Hα emission sources. These sources either were too faint to detect as Hα sources during our Hα survey or were too bright and saturated in the images.

Presumably the most massive star associated with L1188 in our sample is J221643.39+612417.5 ((ADM95) IRAS3) with B3-spectral type (Zakhozhay et al. 2018), a known Hα emission star LS III +61 9 (Wackerling 1970). We identified this star based on its infrared excess, because it was too bright and saturated in our Hα images. This star is located at the outskirts of L1188. Supposedly this star was born at the same time as e.g. the stars of IC 1396. Based on the spectral type estimate most of our young star candidates are K-type stars. It is expected that an important part of the young population is below the detection threshold of the slitless grism spectrograph. The lower mass limit is ~ 0.3 M⊙, corresponding to a spectral type of ~ M3.

4.2.1 Spectral energy distribution

SEDs of the Hα emission stars are shown in Fig. 7, while the SEDs of the infrared excess stars are displayed in Fig. 8. For the Be star we adopted optical magnitudes from Zakhozhay et al. (2018). The dereddened SED and that of the best fitting photosphere are also plotted. The photometry-based effective temperature and extinction are
The average $\dot{M}_{\text{acc}}$ is $8.96 \times 10^{-9} M_\odot$ yr$^{-1}$, a typical value for T Tauri stars.

We fitted the $\dot{M}_{\text{acc}} \propto M^\alpha$ power-law relationship and find a slope $\alpha = 1.55 \pm 0.71$, although the spread is very large in $\dot{M}_{\text{acc}}$ for any $M_*$. The linear fit to the data is,

$$\log \dot{M}_{\text{acc}} = (1.55 \pm 0.71) \log M_* - (8.27 \pm 0.10).$$

Its slope is within the range of recent published values (1.0 to 3.0) for other star-forming regions (Barentsen et al. 2011; Natta et al. 2006, e.g.).

### 4.3 The surface distribution of young stars

The surface distribution of the candidate YSOs (Figs. 3 and 4) reveals two compact groups of young stars. One of them is associated with the westernmost 13CO clump L1188 A, (Ábrahám et al. 1995), and the other one is projected on the 13CO clump L1188 C. A loose aggregate of YSOs is projected on the clump L1188 B. We constructed a surface density map of the YSOs following the method described by Gutermuth et al. (2005). We determined the $r_N(i,j)$ distance of the Nth nearest star at each $(i,j)$ position of a uniform grid and obtained the local surface density of YSOs at the grid point as $\rho(i,j) = N/\pi r^2_N(i,j)$. The surface density contour plot (shown on Figure 9) was constructed using a 30′′ grid and $N = 5$.

#### 4.3.1 Young clusters

To find and characterize clusters in the YSO population of L1188, we used the Minimal Spanning Tree (MST) method presented by Cartwright & Whitworth (2004) and described by Gutermuth et al. (2009) to identify groups. Within the MST structure, clusters can be isolated from the background, when one adopts a critical length longer than the typical separation of cluster members, and shorter than the intermediate spacings between the cluster and background. This critical length was calculated from the cumulative distribution function of the MST branch length. We used a branch length of 150 arcsec to identify the unique clusters within the MST network. In this manner we were able to identify two remarkable clusters. The number of YSO candidates located in these groups is 27 (41.5% of all of the young star candidates). This result is accordance with the surface density map presented in Fig. 9.

One of the two clusters was also identified by Bica et al. (2003) during a hunt for new infrared star clusters based on 2MASS data. This cluster is associated with the DG 180 reflection nebula and consists of 19 young star candidates.
candidates selected mainly based on H$_2$ emission. The [ADM95] IRAS-1 source is also associated with this cluster. The other cluster contains 8 young star candidates, including [ADM95] IRAS-6. The extended, loose aggregate of some 12–15 YSOs, associated with the clump L1188 B and RNO 140 contains the only Class I source of our sample 2MASS J22172227+6143054 and [ADM95] IRAS-4. A compact group of some 10 faint Spitzer sources can be seen in the composite IRAC image of this region, presented in Stolovy et al. (2006). Bica et al. (2003) identify this group as an embedded cluster.

4.3.2 L1188 and the Cepheus Bubble

L1188 is located at the periphery of the Cepheus Bubble. Figure 11 shows the 100μm IRAS (IRIS) image of the
Our selection excluded embed-

sug-

erable with that of Tr 37, the richest subgroup of Cep OB2 (Sicilia-Aguilar et al. 2005). Our selection excluded embed-
ded sources fainter that the Gaia limit at optical wave-

lengths, thus the Class I/Class II number ratio is uncertain.
The large number of candidate YSOs at far larger distances
than L1188 indicates that abundance of Class I protostars,
suggested by Stolovy et al. (2006) and Gong et al. (2017),
may contain sources at various distances. On-going and pos-
sible future star formation in L1188 is indicated by the am-
onia cores (Verebélyi et al. 2013). These cores are located
to the east from the clusters of Class II YSOs. This struc-
ture suggests that star formation proceeds from the west to the
east, according to the triggered star formation scenario.

4.4 Comparison with Other Nearby
Cluster-forming Regions

Gutermuth et al. (2009) studied 36 young clusters within
the 1 kpc of the Sun. Similarly to L1188, most of these star-
forming regions are parts of molecular cloud complexes and
their most massive stars are around 5–6 M⊙ (e.g. IC 348,
NGC 7129, BD+40°4124). Although the known YSO po-

culati on of L1188 is not complete, the number of the YSO

candidates is of the same order of magnitude as of the po-

culation of NGC 7129 or L1211. The MST branch length
of L1188 is also within the range found for this sample.

5 SUMMARY

We studied the little studied young stellar population to-
wards the dark nebulae in L1188. During our slitless grism
Ho survey we found 76 Ho emission line stars, across an area of 60′ × 50′. Based on archival infrared data we iden-
tified further 61 young sources. Finally, we studied the dis-
tance of the sources based on Gaia DR2 data and selected
63 sources related to L1188, nine young star candidates are
background objects (1014–6507 pc) and the distance of
15 sources are unknown. We constructed SEDs of our tar-
get stars associated with L1188 based on Pan-STARRS,
2MASS, WISE and Spitzer photometric data, derived their
spectral types, extinctions, estimated masses by pre-main se-
quence evolutionary models, and examined the disc shapes
utilizing the 2–24 μm interval of the SED. We measured
the equivalent width of the Hα line for a subsample of our targets and derived accretion rates. The average $M_{\text{acc}}$ is $8.96 \times 10^{-9} \, M_\odot \, \text{yr}^{-1}$. The new extinction map of L1188, based on Pan-STARSS data, reveals a filamentary structure, with very compact, high density regions. We found that star formation in L1188 started about 5 million years ago. The age of the newly identified pre-main-sequence population is comparable to that of the nearby Trumpler 37. The L1188 star-forming region was probably created during the fragmentation of the shell, compressed by the expanding ionization front and stellar wind of the Cep OB2a association (Patel et al. 1998). Collision of clouds, proposed by Gong et al. (2017), might have played a role in star formation. The presence of young clusters outside the proposed collision region, however, suggests further agents. The apparent age gradient of star formation signposts across the cloud supports the role of the expansion of the Cepheus Bubble.

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Figure 9. Surface density distribution of the young stars, overplotted on the DSS2 red image of the cloud, centered on R.A.(2000) = 22h 17.5m and Dec(2000) = 61° 42′. Red contours show the surface density of the young star candidates. The dashed squares show the regions displayed in Fig. 10. The distribution was computed from the distance of the fifth-nearest stars to the grid points.

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Figure 10. Composite images of the two identified clusters using *WISE* 3.6, 12 and 22 µm images. Left: the cluster around DG 180, red squares indicate the young star candidates, while solid black circle shows the region identified by Bica et al. (2003) as an infrared cluster. Right: the cluster around the [ADM95] IRAS-6 source.

Figure 11. IRAS 100 µm(IRIS) image of the Cepheus Bubble. Blue diamonds are *WISE* YSO candidates presented by Marton et al. (2016), while red crosses represent young star candidates belonging to L1188. The area bordered by the black squares was the target of our Hα survey.

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Table 2. Hα emission line stars associated with L1188

| Name              | 2MASS ID          | EW(Hα)(Å)     | r'PHAS (mag) | SED            |
|-------------------|-------------------|---------------|--------------|----------------|
| L1188 Hα 2        | J22140899+6130163 | 10.56 ± 4.51  | 17.18 ± 0.01 | Class II       |
| L1188 Hα 3        | J22141156+6126063 | 27.08 ± 2.77  | 17.56 ± 0.01 | Class II       |
| L1188 Hα 5        | J22142723+6129433 | 60            | 19.39 ± 0.06 | Flat           |
| L1188 Hα 6        | J22142746+6126103 | 22.29 ± 5.13  | 17.53 ± 0.01 | Flat           |
| L1188 Hα 7        | J22142761+6126200 | 60            | 20.98 ± 0.23 |               |
| L1188 Hα 8        | J22142828+6125239 | 60            | 17.68 ± 0.01 | Flat           |
| L1188 Hα 10       | J22143014+6132132 | 17.86 ± 9.36  | 18.47 ± 0.03 |               |
| L1188 Hα 11       | J22143983+6127304 | 60            | 19.72 ± 0.08 |               |
| L1188 Hα 13       | J22143917+612216  | 60            | 17.48 ± 0.01 | Flat           |
| L1188 Hα 15       | J22143646+6124439 | 60            | 19.05 ± 0.04 | Flat           |
| L1188 Hα 18       | J22143799+6128060 | 60            | 19.66 ± 0.07 | Class II       |
| L1188 Hα 19       | J22143816+6125514 | 70            | 20.03 ± 0.10 |               |
| L1188 Hα 20       | J22143844+6125019 | 33.22 ± 4.37  | 16.91 ± 0.01 | Flat           |
| L1188 Hα 23       | J22143941+6125427 | 76.98 ± 30.22 | 19.97 ± 0.09 | Flat           |
| L1188 Hα 25       | J22143982+6125587 | 40            | 17.68 ± 0.01 | Flat           |
| L1188 Hα 26       | J22144089+6126451 | 60            | 20.27 ± 0.12 | Class II       |
| L1188 Hα 27       | J22144156+6124100 | 16.27 ± 1.94  | 16.28 ± 0.01 | Class II       |
| L1188 Hα 28       | J22144218+6125251 | 20            | 18.18 ± 0.02 | Class II       |
| L1188 Hα 29       | J22144343+6128192 | 85.92 ± 85.48 | 20.17 ± 0.11 | Class II       |
| L1188 Hα 31       | J22145213+6131052 | 20            | 19.46 ± 0.06 | Class II       |
| L1188 Hα 32       | J22145479+6128328 | 45            | 19.93 ± 0.09 |               |
| L1188 Hα 33       | J22150238+6132443 | 97.37 ± 25.84 | 20.70 ± 0.18 | Class II       |
| L1188 Hα 36       | J22150844+6131551 | 20            | 18.50 ± 0.03 | Class II       |
| L1188 Hα 43       | J22162418+6159190 | 60            | 18.57 ± 0.03 | Class II       |
| L1188 Hα 44       | J22170839+6131063 | 38.71 ± 6.02  | 16.54 ± 0.01 | Class II       |
| L1188 Hα 47       | J22172174+6140405 | 20            | 18.65 ± 0.03 | Class II       |
| L1188 Hα 48       | J22172227+6143054 | 60            | 18.86 ± 0.03 | Class I        |
| L1188 Hα 51       | J22174025+6147025 | 122.69 ± 15.36| 17.34 ± 0.01 | Class I        |
| L1188 Hα 52       | J22174140+6143525 | 60            | 19.05 ± 0.04 | Class II       |
| L1188 Hα 53       | J22174489+6141310 | 56.99 ± 31.12 | 18.46 ± 0.03 | Class II       |
| L1188 Hα 54       | J22183014+6137582 | 60            | 18.54 ± 0.03 | Class II       |
| L1188 Hα 55       | J22181032+6150416 | 14.37 ± 3.85  | 17.95 ± 0.02 | Class II       |
| L1188 Hα 56       | J22181140+6155570 | 10            | 17.18 ± 0.01 |               |
| L1188 Hα 57       | J22182573+6137265 | 60            | 18.45 ± 0.03 | Class II       |
| L1188 Hα 58       | J22184051+6137298 | 29.39 ± 4.41  | 16.07 ± 0.01 | Class II       |
| L1188 Hα 60       | J22190050+6136265 | 58.57 ± 15.13 | 17.97 ± 0.02 | Class II       |
| L1188 Hα 62       | J22190298+6136208 | 60            | 18.66 ± 0.03 |               |
| L1188 Hα 64       | J22190442+6136250 | 84.54 ± 18.07 | 17.68 ± 0.02 | Flat           |
| L1188 Hα 66       | J22190554+6136156 | 60            | 18.03 ± 0.02 | Class II       |
| L1188 Hα 69       | J22190950+6137587 | 40.46 ± 7.13  | 17.66 ± 0.02 | Class II       |
| L1188 Hα 75       | J22141290+6141164 | 60            | 18.12 ± 0.02 | Class II       |
### Table 3. Young stars identified based on infrared excess

| Name                                      | SED               |
|-------------------------------------------|-------------------|
| 2MASS J22144030+6126137                    | Class II          |
| AllWISE J221454.81+614224.6                | Flat              |
| AllWISE J221504.18+613917.1                | Class II          |
| 2MASS J22151924+6136523                     | Class II          |
| SSTSL2 J221521.04+614827.3                 | Class II          |
| SSTSL2 J221559.25+613536.3                 | Class II          |
| SSTSL2 J221605.94+613553.9                 | Class II          |
| SSTSL2 J221627.88+614047.7                 | Class II          |
| SSTSL2 J221643.39+612417.5                 | Class II          |
| SSTSL2 J221658.12+614620.4                 | Class II          |
| SSTSL2 J221703.22+613714.8                 | Class II          |
| SSTSL2 J221709.59+614111.5                 | Flat              |
| SSTSL2 J221725.49+614302.0                 | Class II          |
| SSTSL2 J221728.74+614150.8                 | Class II          |
| SSTSL2 J221742.77+613133.2                 | Class II          |
| AllWISE J221744.97+615337.0                | Class II          |
| AllWISE J221746.09+613925.1                | Class II          |
| AllWISE J221801.53+614030.1                | Class II          |
| AllWISE J221906.32+613553.1                | Class II          |
| AllWISE J221913.72+613745.6                | Class II          |
| AllWISE J221914.68+613847.3                | Class II          |
| AllWISE J222300.37+615721.2                | Flat              |
Table 4. Young star candidates, possibly associated with L1188

| Name                                      | Distance (pc) | SED   |
|-------------------------------------------|---------------|-------|
| SSTSL2 J221723.20+614953.2               | · · ·         | Class I |
| SSTSL2 J221726.28+614218.9               | · · ·         | Class I |
| SSTSL2 J221732.42+614152.6               | · · ·         | Class I |
| Name                     | Distance (pc) | SED       | Cross Id.  |
|-------------------------|--------------|-----------|------------|
| J22140180+6129208       | 1164 ± 3487  | L1188 Hα 1|
| J22141165+6156281       | 3753 ± 4716  | L1188 Hα 4|
| J22142611+6127246       | 2997 ± 3010  | Flat      |
| J22142908+6126025       | 3134 ± 3046  | Class I   |
| J22142921+612741.9      | 3844 ± 2494  | Flat      |
| J221429.73+612539.2     | 3567 ± 2870  | Flat      |
| J22143129+6127587       | 1298 ± 193   | Flat      |
| J22143312+6129374       | 1598 ± 3002  | Flat      |
| J22143682+6150250       | 1292 ± 250   | Flat      |
| J22143714+6126246       | 2334 ± 1701  | Class I   |
| J22143859+6124377       | 625 ± 138    | Flat      |
| J22143856+6127511       | 3300 ± 1465  | Class II  |
| J22145152+6140127       | ...           | Class II  |
| J22150364+6129297       | 502 ± 198    | Flat      |
| J22153114+6155278       | 3312 ± 1167  | Class II  |
| SSTSL2 J221543.96+615228.0 | 1253 ± 3225 | Class II  |
| J22155762+6135463       | 3931 ± 1878  | Flat      |
| J22154943+6136464       | 1188 ± 521   | Class II  |
| J22160406+6136151       | 1243 ± 158   | Class II  |
| J22161536+6133101       | 4000 ± 2453  | Class II  |
| SSTSL2 J221615.78+612948.6 | ...         | Class II  |
| SSTSL2 J221619.76+612948.3 | ...         | Class II  |
| SSTSL2 J221643.09+613819.7 | 3466 ± 3443 | Class II  |
| AIWISE J221646.89+613363.4 | 4707 ± 1427 | Class II  |
| SSTSL2 J221653.13+614315.5 | ...         | Class II  |
| AIWISE J221703.85+620455.9 | ...         | Class II  |
| SSTSL2 J221707.87+615039.4 | 3346 ± 3037 | Class II  |
| SSTSL2 J221708.55+614127.1 | 2639 ± 1358 | Class II  |
| SSTSL2 J221715.75+615208.0 | 3348 ± 1397 | Class II  |
| SSTSL2 J221716.31+614110.2 | 1740 ± 2463 | Class II  |
| J22171752+6138199       | 3277 ± 268   | Class II  |
| AIWISE J221718.87+614232.7 | 469 ± 238  | Class II  |
| SSTSL J221719.56+614303.7 | 1014 ± 3303 | Class II  |
| J22172039+6116469       | 2942 ± 1317  | Class II  |
| SSTSL2 J221723.32+614231.3 | ...         | Class II  |
| J22172625+6139930       | 3235 ± 3034  | Class II  |
| SSTSL2 J221726.53+614239.9 | ...         | Class II  |
| SSTSL2 J221726.56+614814.6 | 3054 ± 1496 | Class II  |
| SSTSL2 J221726.92+614811.0 | 2392 ± 1323 | Class II  |
| AIWISE J221727.07+614217.7 | ...         | Class II  |
| J22172826+6145172       | 658 ± 268    | Class II  |
| SSTSL2 J221732.19+613854.7 | 1823 ± 208  | Class II  |
| SSTSL2 J221734.54+613928.3 | 3453 ± 397  | Class II  |
| SSTSL2 J221736.38+612715.1 | 1444 ± 329  | Class II  |
| SSTSL2 J221737.18+614312.4 | ...         | Class II  |
| SSTSL2 J221738.26+614146.2 | ...         | Class II  |
| SSTSL2 J221743.66+612657.7 | 1464 ± 187  | Class II  |
| AIWISE J221745.90+615433.3 | ...         | Class II  |
Table 5 – continued

| Name                  | Distance (pc) | SED    | Comment  |
|-----------------------|---------------|--------|----------|
| AllWISE J221748.98+615514.9 | 2963 ± 8039 | Class I |          |
| SSTSL2 J221808.26+613132.5  | 1506 ± 516 | Class II |          |
| J22185005+6122062       | 4942 ± 6057 |        | L1188 Hα 59 |
| J22190065+6136384       | ...          |        | L1188 Hα 61 |
| J22190317+6137563       | 581 ± 153 | Class II | L1188 Hα 63 |
| J22190443+6136486       | 627 ± 66  | Class II | L1188 Hα 65 |
| J22190876+6137075       | 718 ± 2370 |        | L1188 Hα 67 |
| J22190879+6137329       | 1121 ± 162 | Class II | L1188 Hα 68 |
| J22192196+6137305       | 1338 ± 418 | Class II | L1188 Hα 70 |
| J22192789+6158582       | 1891 ± 1653 | Class II | L1188 Hα 71 |
| AllWISE J221940.96+612219.8 | 1061 ± 228 | Flat |          |
| AllWISE J221945.24+612437.1 | 6507 ± 1628 | Class II |          |
| J22201557+6159403       | 654 ± 84  | Class II | L1188 Hα 73 |
| J22210934+6120172       | 2494 ± 1701 |        | L1188 Hα 74 |
| AllWISE J222422.33+613058.6 | 3497 ± 349  | Class II |          |
| AllWISE J222223.69+613252.0 | 1364 ± 87  | Class II |          |
| J22222816+6154392       | 236 ± 6   |        | L1188 Hα 76 |