A new look at Sco OB1 association with Gaia DR2

L. Yalyalieva,1,2,3⋆ G. Carraro,3 R. Vazquez,4 L. Rizzo,4 E. Glushkova,1,2 and E. Costa5

1Physics Department, Lomonosov Moscow State University, Leninskie Gory, Moscow, 119991, Russian Federation
2Sternberg Astronomical Institute, Lomonosov Moscow State University, Universitetskij pr.13, Moscow, 119234, Russian Federation
3Department of Physics and Astronomy, Padova University, Vicolo Osservatorio 3, I-35122, Padova, Italy
4Instituto de Astrofísica de La Plata (CONICET, UNLP), Paseo del Bosque s/n, La Plata, Argentina
5Departamento de Astronomia, Universidad de Chile, Casilla 36-D, Santiago, Chile

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ABSTRACT

We present and discuss photometric optical data in the area of the OB association Sco OB1 covering about 1 squared degree. UBVI photometry is employed in tandem with Gaia DR2 data to investigate the 3 dimensional structure and the star formation history of the region. By combining parallaxes and proper motions we identify 7 physical groups located between the young open cluster NGC 6231 and the bright nebula IC4628. The most prominent group coincides with the sparse open cluster Trumpler 24. We confirm the presence of the intermediate age star cluster VdB-Hagen 202, which is unexpected in this environment, and provide for the first time estimates of its fundamental parameters. After assessing individual groups membership, we derive mean proper motion components, distances, and ages. The seven groups belong to two different families. To the younger family (family I) belong several pre-Main Sequence stars as well. These are evenly spread across the field, and also in front of VdB-Hagen 202. VdB-Hagen 202 and two smaller, slightly detached, groups of similar properties form family II, which do not belong to the association, but are caught in the act of passing through it. As for the younger population, this forms an arc-like structure from the bright nebula IC 4628 down to NGC 6231, as previously found. Moreover, the pre-Main Sequence stars density seems to increase from NGC 6231 northward to Trumpler 24.

Key words: star clusters and association: general – star clusters and associations: individual: Trumpler 24, VdB-Hagen 202

1 INTRODUCTION

According to (Lada & Lada 2003) most stars form in relatively compact clusters with more than 100 members. In this scenario stellar associations, namely loose groups of stars of early spectral types, are interpreted as the early stages of dynamical dissolution of star clusters. This process is referred to as infant mortality, and it is triggered by gas expulsion from stellar winds and, probably, SNae events. Therefore, stars clusters would form embedded in molecular clouds and bound, but the largest part of them will quickly expand and then slowly dissolve. This paradigm has been recently challenged by a detailed study of nearby stellar associations using Gaia DR2 data (Ward et al. 2019). Most associations in fact do not show any expansion signatures confirming earlier results by (Mel’nik & Dambis 2018). Besides, associations are unbound loose ensembles containing a sizeable fraction of OB stars (Efremov 1989), and are organised in fractal structures (Gouliermis 2018), going from associations to aggregate, and then complexes and super-complexes. Their existence, young age, and structure should contain imprints of their recent formation. Therefore, detailed studies of individual star 3-dimensional structure, age, and kinematics are essential to understand their formation and, in turn, to constrain the star formation process better (Beccari et al. 2018).

With the aim of providing additional insights on this important topic, in this paper we investigate an area of one degree on a side in the Sco OB1 association, centred at α = 253°.97, δ = −40°.64 (Fig. 1), for which we secured multi-band optical photometry. Sco1 is a very rich and complex stellar association (Damiani 2018). The spectacular H II region G345.45+1.50 is situated in the northern part of the field, while the most prominent young star cluster, NGC 6231 (Baume et al. 1999; Feinstein et al. 2003; Sung et al. 1998, 2013), is located in the southern part. We are not covering this cluster in our study, but we are concentrating

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on the northern and central region. Here, the most interesting structure is Trumpler 24. This is thought to be a young open cluster with poorly defined boundaries and complex structure belonging to Sco OB1 (Heske & Wendker 1984). Besides, the area under investigation is rich in pre-main sequence stars (Heske & Wendker 1984; Damiani 2018), which indicates active/recent star formation.

Because of the presence of a lot of gas irregularly distributed which causes a significant differential reddening, photometry is not enough to identify known and/or unknown stellar groups and determine their population. For this reason, we complement our photometric data-set with the high quality astrometric data from Gaia DR2 (Gaia Collaboration et al. 2018). To this aim we recall the reader that recently a number of special tools and approaches for group searching and assigning membership probabilities was constructed, including clustering methods (Krone-Martins & Moitinho 2014) and unsupervised learning algorithms (Tang et al. 2019; Yuan et al. 2018). Initial data could be of different types: researches could use only photometry (Buckner & Froebrich 2013), only astrometry (Cantat-Gaudin et al. 2019) or combine these two sources (Krone-Martins & Moitinho 2014).

Therefore, the layout of the paper is as follow: in Section 2 we describe our photometric observation. Section 3 is dedicated to the detection of stellar groups in the area. We discuss the population of PMS stars in the region in Section 4 Finally, Section 5 summarises our findings.

2 OBSERVATIONS AND DATA REDUCTION

Trumpler 24 was originally observed at Las Campanas Observatory (LCO) on the nights of August 12 and 13, 2016, using the 1-m Henrietta Swope Telescope1. The camera employed for direct CCD imaging in the $UBV_{I}$ pass-bands was the E2V CCD231-#84 one ($4096 \times 4112$ pixels), with a scale of $0.435''/pixel$ and a field-of-view (FOV) of $29.7'' \times 29.8''$. The CCD was operated without binning at a nominal gain of $1.04e^-$/ADUs, implying thus a readout noise of $3.4e^-$ per quadrant.

Along the two observing runs, named N1 and N2, we needed five target fields to properly cover the whole area of Trumpler 24; they are indicated Tr24$_1$, Tr24$_2$, etc, in Fig. 2 and Table 1, respectively. As can be seen in Fig.2 there is enough overlapping ($3''$ to $5''$) amongst the different frames. The observations were carried out under reasonable seeing conditions (always less than $1.5''$).

The transformation from instrumental system to the standard Johnson-Kron-Cousins system, as well as corrections for atmospheric extinction, were determined through multiple observations of standard stars in Landolt areas G93-48, PG2213-006, and TPHE (Landolt 2009). To this aim, these stars were observed at air mass ranging from 1.06 to 2.12 approximately for both nights. As for the colour coverage, the standard stars sweep a range of $-0.29 \leq B-V \leq 1.55$ and $-1.22 \leq U-B \leq 1.87$, therefore very suitable for a young stellar region as Trumpler 24 is assumed to be.

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Basic calibration of the scientific CCD frames was done using IRAF package CCDRED. For this purpose, zero

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1 http://www.lco.cl/telescopes-information/herrietta-swope

Figure 1. A Digital Sky Survey image of the Sco OB1 area. The white solid polygon encloses the field covered by our photometry (see also Fig. 2). The conspicuous star cluster in the south-west is NGC 6231, while the norther part is dominated by the H II region G345.45+1.50. Several bright, probably early type stars are spread across the field.

Figure 2. Calibrated CCD frames, numbered as in Table 1, to show the quality of the images and the actual field coverage.
Table 1. UBVI photometric observations of the 5 target fields.

| Target | Date | Filter | Exposure(s) | airmass |
|--------|------|--------|-------------|---------|
| Tr24_1 | N1   | U      | 60,300      | 1.035 - 1.038 |
|        |      | B      | 30,200      | 1.042 - 1.043 |
|        |      | V      | 15,150      | 1.046 - 1.048 |
|        |      | I      | 15,100      | 1.029 - 1.030 |
| Tr24_2 | N2   | U      | 60,300      | 1.020 - 1.021 |
|        |      | B      | 30,200      | 1.020 - 1.021 |
|        |      | V      | 15,100      | 1.020 - 1.020 |
|        |      | I      | 15,100      | 1.021 - 1.021 |
| Tr24_3 | N1   | U      | 60,300      | 1.024 - 1.025 |
|        |      | B      | 30,200      | 1.021 - 1.021 |
|        |      | V      | 15,100      | 1.022 - 1.022 |
|        |      | I      | 15,100      | 1.026 - 1.026 |
| Tr24_4 | N2   | U      | 60,300      | 1.024 - 1.024 |
|        |      | B      | 30,200      | 1.021 - 1.021 |
|        |      | V      | 15,100      | 1.022 - 1.022 |
|        |      | I      | 15,100      | 1.026 - 1.026 |
| Tr24_5 | N1   | U      | 60,300      | 1.020 - 1.021 |
|        |      | B      | 30,200      | 1.019 - 1.019 |
|        |      | V      | 15,100      | 1.020 - 1.021 |
|        |      | I      | 15,100      | 1.022 - 1.023 |

Table 2. UBVI photometric observations of standard stars.

| Target   | Date | Filter | Exposure(s) | airmass |
|----------|------|--------|-------------|---------|
| G93-48   | N1   | U      | 2x200       | 1.34 - 2.00 |
|          |      | B      | 3x60        | 1.18 - 2.14 |
|          |      | V      | 2x40        | 2.08 - 2.10 |
|          |      | I      | 3x30        | 1.18 - 2.12 |
|          |      | N2     | 3x200       | 1.17 - 2.01 |
|          |      | B      | 2x60,40     | 1.17 - 2.07 |
|          |      | V      | 3x40        | 1.17 - 2.12 |
|          |      | I      | 3x30        | 1.17 - 1.92 |
| PG1213-006A | N1 | U      | 3x200       | 1.14 - 1.86 |
|           |      | B      | 3x60        | 1.15 - 1.74 |
|           |      | V      | 3x40        | 1.14 - 1.77 |
|           |      | I      | 3x30        | 1.14 - 1.92 |
|           |      | N2     | 4x200       | 1.14 - 2.00 |
|           |      | B      | 4x60        | 1.14 - 1.88 |
|           |      | V      | 4x40        | 1.14 - 1.92 |
|           |      | I      | 4x30        | 1.14 - 2.06 |
| TPHE     | N1   | U      | 60,100      | 1.07 - 1.08 |
|          |      | B      | 40,80       | 1.10 - 1.10 |
|          |      | V      | 30,60       | 1.09 - 1.09 |
|          |      | I      | 10,30       | 1.08 - 1.08 |
|          |      | N2     | 200         | 1.06 - 1.06 |
|          |      | B      | 20,60,80    | 1.06 - 1.07 |
|          |      | V      | 5,20,60     | 1.07 - 1.07 |
|          |      | I      | 5,10,30     | 1.06 - 1.06 |

Table 3. Extinction coefficients

| Night | u1 | u2 | b1 | b2 |
|-------|----|----|----|----|
| N1    | 3.89±0.04 | -0.29±0.01 | 1.82±0.01 | -0.08±0.01 |
| N2    | 3.83±0.02 | -0.30±0.01 | 1.90±0.01 | -0.08±0.01 |

The transformation equations to put instrumental magnitudes into the UBVI standard system were of the form:

\[ u = U + u_1 + u_2 \times X + u_3 \times (U - B) \]
\[ b = B + b_1 + b_2 \times X + b_3 \times (B - V) \]
\[ v = V + v_1 + v_2 \times X + v_3 \times (B - V) \]
\[ i = I + i_1 + i_2 \times X + i_3 \times (V - I) \]

where \( u_2, b_2, v_2 \) and \( i_2 \) are the extinction coefficients for the UBVI bands, \( X \) is the air mass for each exposure and \( u_1, b_1, v_1, i_1, u_3, b_3, v_3, \) and \( i_3 \) are the fitted parameters. As said, extinction coefficients were computed for each night. Final photometric tables will be made available at CDS.

The point-spread function (PSF) method (Stetson 1987). Aperture corrections were then determined, making aperture photometry of a suitable number of well isolated stars (typically 20 to 90) all above the target fields. Typically these corrections were found to vary from 0.14 to 0.31 mag, depending on the filter. The PSF photometry was finally aperture corrected, filter by filter.

Finally, the transformation from pixels (i.e., detector-coordinates) to equatorial right ascension and declination for the equinox J2000.0 was performed using Gaia DR2 (Gaia Collaboration et al. 2018) coordinates of 98 brightest stars in the field. The number of stars detected in the V and B filters amount at 21196. Among them 8719 stars have counterparts in the U filter and 20960 in the I filter. The completeness limits for each filter are \( U_{lim} = 18.7, B_{lim} = 19.9, \) \( V_{lim} = 18.2, \) and \( I_{lim} = 20.2. \)

The resulting catalog was cross-correlated with Gaia DR2 (Gaia Collaboration et al. 2018) data with 1.5° radius of cross-correlation (for 93 per cent of objects angular distance between sources turned out to be less then 0.4°). Taking into account the point-spread function (PSF) method (Stetson 1987).

exposure frames and twilight sky flats were taken every night. All frames were pre reduced, applying trimming, bias, and flat-field correction. Before flat-fielding, all frames were corrected for linearity, following the recipe discussed in Hamuy et al. (2006). Photometry was then performed using the IRAF DAOPHOT/ALLSTAR and PHOTCAL packages. Instrumental magnitudes were extracted following

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consideration parallaxes and using isochrones Marigo et al. (2017) we calculated an approximate mass limit of 0.85-1.0 $M_\odot$. The number of matches with Gaia was 21172 objects, but only objects with errors in parallaxes being less than 20% were kept for the following analysis, so the number of objects in the final catalogue tuned out to be 11506 objects.

3 DATA ANALYSIS, PHYSICAL GROUPS AND THEIR PROPERTIES

In this Section we describe how stellar groups are identified, and how individual membership has been assessed. Then, properties of the various groups are derived.

3.1 The clustering algorithm

We applied a clustering algorithm in a 5-dimensional space using equatorial coordinates, proper motion components and parallaxes. We should mention that in the framework of clustering methods the term cluster does not refer to a physically bound star cluster but to a set of objects sharing common properties and clustering in a N-dimensional coordinate space. We will call the outcome of the clustering algorithm a cluster or a group, and use the term star cluster for physical astronomical objects.

The clustering algorithm here adopted is based on the DBSCAN (Density-Based Spatial Clustering of Applications with Noise) technique. The algorithm was implemented in Python language and uses clustering module of machine learning library scikit-learn (Pedregosa et al. 2011) as its basis. One of the main features of DBSCAN is that it considers clusters as a set of core points in the neighbourhood of each other, non-core points in the neighbourhood of core points and noise. So, in comparison with other commonly used methods, such as k-means and affinity propagation methods, DBSCAN has an important advantage, namely that part of the points are considered to be noise, non-members of clusters. This feature was one of the crucial points when choosing DBSCAN as the best method for our purposes.

DBSCAN requires numeric values of two parameters: (1) $\varepsilon$ - maximum distance between two points to label that one is in the neighbourhood of the other and (2) $N$ - number of points in a neighbourhood of a point to label it as a core point. The choice of the parameters was performed the following way:

(a) Testing parameters from wide intervals: (0.01-0.99) and (10-60) for the first ($\varepsilon$) and the second ($N$) parameter, correspondingly. Lower limit for $N$ was chosen in agreement with Schubert et al. (2017), where it is recommended to adopt $N$ values which are not less than twice the value of dimensions of the data. As in the present work clustering is performed in 5-dimensional space, the minimum value of $N$ is 10.

(b) Choosing parameters which lead to a maximum number of clusters: $\varepsilon=0.17$, $N=10$.

In order to get probability of each star to be a cluster member and to take into account errors of observables, the clustering algorithm was applied 1000 times. In each run data was altered by adding random value extracted from a normal distribution with the mean value equals to original data and dispersion equals to error. Errors were taken individually, so for each star parameters were taken from individual distributions. The average mean values of proper motions errors are $e_{\mu_\alpha}=0.25$ mas year$^{-1}$, $e_{\mu_\delta}=0.17$ mas year$^{-1}$ and mean error of parallaxes are $e_{plx}=0.13$ mas. Membership probability was then determined according to the number of events when a star was labeled as a member of a cluster divided by the number of runs ($1000$).

Before the application of the above mentioned algorithm, data were transformed using principal component analysis (PCA) to eliminate correlations between observables. PCA constructs an orthogonal coordinate system in such a way that all the subsequent principal components have the largest variance and are orthogonal to the previous ones: the first principal component has the largest variance, the second has the largest variance and orthogonal to the first one, and so forth. Then all principal components were scaled to unit variance.

As a result of the clustering algorithm we obtained seven groups with stars having membership probability of more than 50 per cent (Fig. 3). For members of groups B (which we subdivided into B1, B2, and B3 subgroups) and A the probability is larger than 90 per cent and 98 per cent, correspondingly, according to probability distribution peaks. For all of these groups we estimated fundamental properties: age, reddening, distance and mean proper motion. Distances were obtained by two independent ways: with the use of photometry alone, and from Gaia DR2 parallaxes.

![Detected groups in the covered Sco OB1 association region and comparison with known or suggested groups from Simbad. See text for details.](image-url)
3.2 Photometric distances

We adopted a zero-age main sequence (ZAMS) from Turner (1996) to estimate reddening and distance modulus by fitting theoretical ZAMS to our data in \((B - V)\) vs. \((U - B)\) colour-colour and \((B - V)\) vs. \(V\) colour-magnitude diagrams respectively (Fig. A1 and Fig. B1 in Appendix). The region of Sco OB1 association is highly affected by variable reddening (Damiani 2018) and probably affected too by differential extinction. To obtain more precise results we derived inclinations of reddening vectors and ratios of total-to-selective absorption \(R_V = A_V/E(B - V)\) in the direction of each group. We performed a weighted least squares fit in \((V - I)\) vs. \((B - V)\) colour-colour diagram, where stars are distributed almost parallel to the reddening vector. Then we used a parametrisation for optical/NIR wavelengths regions as described in Cardelli et al. (1989) and obtained values of \(R_V\) and \((U - B)/(B - V)\). The resulting values of \(R_V\) toward the direction of each group are listed in Table 4. Reddening \(E(B-V)\) is then derived from the colour-colour diagram in a standard way (Carraro 2011).

3.3 Astrometric distances

Different estimations of the zero-point offset of Gaia parallaxes have been recently found. In the paper by Lindegren et al. (2018) a claim is made for a zero-point offset of 0.03 mas, but there are evidences that it is larger. Zinn et al. (2019) estimated a value of about 0.053 mas using red giant branch stars from the APOKASC-2 catalog. Riess et al. (2018) obtained a value of 0.046 ± 0.009 mas using bright extragalactic Cepheids. All of them indicate that Gaia parallaxes are underestimated. Here we used the value of offset of 0.045 ± 0.009 mas (Yalyalieva et al. 2018) obtained from comparison of parallaxes from photometry study of young open clusters in the northern sky with their parallaxes from Gaia. We applied kernel density estimator to parallax distribution. We used Gaussian as a kernel with the optimal bandwidth found from cross-validation algorithm individually for each cluster. To take into account individual errors of parallaxes, we added weights to each point equals to \(1/\sigma^2\), where \(\sigma\) is the error of parallax of each star. Although for our analysis we selected stars with errors in parallaxes less than 20%, errors for stars belonging to groups are much less - mean error of parallaxes ranges form 6% for C group to 11% or D group. The outcome of kernel density estimation was fitted with Gaussian distribution, then stars out of 2\(\sigma\) were removed. This \(\sigma\)-clipping procedure was repeated until convergence. When the number of stars in the group was not enough for statistics, the mean value was adopted. To take into account the error of zero-point offset we shifted parallaxes to ±0.009 mas and repeated Gaussian fitting in...
the way mentioned above. The resulting estimated error of mean distance to group is considered to be interval between mean values of shifted parallaxes with added errors from the Gaussian fit.

A comparison between photometric and astrometric distances is shown in Fig. 4. There is a generally good agreement between the two different estimates, except for group E. Because of the global good agreement we will adopt in the following the astrometric distance for group E as well. This is supported also by the fact that group E shares all the other properties (age and kinematics) with groups A and F, and also because the photometric distance estimate could be affected by low number statistics.

3.4 Ages

Ages for groups A, B, C, F and G were estimated by fitting theoretical PARSEC + COLIBRI isochrones (Marigo et al. 2017) on the data in the colour-magnitude diagram (B − V) vs. V (see Appendix B1). Isochrones were previously shifted by the values of colour excess E(B − V) and distance modulus (m − M)_V, obtained from ZAMS fitting. Resulting ages are listed in the Table 4.

Group A: about 60% of the stars are non-ZAMS, with 5 evolved stars in the red clump around (B − V) ≈ 1.7 and V ≈ 13. ZAMS stars are the stars that are fainter than \(V \approx 15.5\) and redder than (B − V) ≈ 0.9.

Group B1: group of 29 young stars, about 75% of them are PMS stars, ZAMS stars could be found in the colour range \(0.15 \leq (B − V) \leq 0.3\) and with magnitudes \(11.5 \leq V \leq 12.8\).

Group B2: about 70% of 32 stars are PMS stars with some spread in ages, ZAMS stars have colours about \(0.2 \leq (B − V) \leq 0.4\) and magnitudes in V filter about \(12 \leq V \leq 14\).

Group B3: like in the cases of B1 and B2 groups, the number of ZAMS stars is about 1/3, and they have colours \(0.2 \leq (B − V) \leq 0.5\) and magnitudes \(11.2 \leq V \leq 14.3\). The remaining 70-75% of 27 stars are PMS stars.

Group C: 5 out of 9 stars are supposed to be ZAMS stars in the range of \(0.4 \leq (B − V) \leq 0.6\) and \(12.5 \leq V \leq 14\), and 4 stars are PMS.

Group F: a small group of 10 stars, 3 of them are on ZAMS (\(0.3 \leq (B − V) \leq 0.45, 11.7 \leq V \leq 13.4\)). 7 PMS stars are scattered, causing some ambiguity in ages.

Group G: a group numbers 41 objects, about 34% are on ZAMS in the following ranges: \(0.2 \leq (B − V) \leq 0.55\) and \(11 \leq V \leq 13.9\). Groups D and E are not rich enough in bright stars and isochrones fitting could lead to inaccurate results. In these two cases we estimated ages of the brightest stars still in MS and adopted them as ages of the groups.

3.5 Mean proper motions

Mean proper motion components were estimated via a clipping method, and removing stars beyond 3σ threshold. They are shown in the vector point diagram (lower panel of Fig. 5). Proper motion components seem to form two distinct groups. We also computed the tangential velocities, which are shown in the upper panel of the same Figure, where we indicate both the direction and the size of the proper motion vectors for each star in the various groups. The solid black arrow in the figure indicates the scale of tangential velocities. Also in this panel two separate groups are visible. Mean proper motion components and tangential velocities of groups are listed in Table 5.

3.6 Group by group properties

In the Table 4 and Table 5 we presented parameters of groups estimated from photometry and from Gaia data, respectively. For most groups only stars with more than 50 per cent probability were kept, except for the richest A and B groups where the threshold was enhanced to 98 per cent and 90 per cent respectively in accordance with peaks of the probability distributions. Table 4 also includes (last two columns) the tangential velocity \(v_T\) and the associated uncertainty.
our study. We suggest these two latter are most probably spurious detections.

Finally, our groups C, D, E, and F are not present in SIMBAD. In Table 6 we listed coordinates of the SIMBAD objects and some of their physical properties (distance, age, proper motion) as taken from Dias et al. (2002).

Group A
Group A clearly coincides with VdB-Hagen 202 (van den Bergh & Hagen 1975), who describe it as a poor, possibly embedded cluster. It also corresponds to (Sseggewiss 1968) group Trumpler 24 I. It is the richest group detected in the area. It has also the largest tangential velocity and the largest age. The isochrone fit yields a 500 million year, while both the astrometric and the photometric analysis support a heliocentric distance of 1.65 kpc. This group has not been detected by (Damiani 2018), possibly because it does not contain young M stars. On the other hand, close to this position (Kuhn et al. 2019) found two rich groups (3 and 5, according to their numbering) of young stars slightly to the north of our group A. In any case, the large age and tangential motion lends additional support to a picture in which this cluster does not belong to the association, but it is probably caught in the act of passing through it. The groups D and E (see below) share the same properties of this group A.

Group B
This group is situated in the southern edge of the H II region G345−1.50, and appears quite scattered. DBSCAN returns three density peaks, that we indicate as B1, B2, and B3, but the area roughly corresponds to Trumpler 24. (Sseggewiss 1968) also identified this group, which he indicated as group Trumpler 24 III. It is separated by a gap from the other groups identified in this study. Beside the location, these 3 groups share the same age and kinematics. In the literature, Trumpler 24 distance ranges from 1.6 to 2.2 kpc (Sseggewiss 1968; Heske & Wendker 1984). Our study favours the shortest distance, both from photometry and from Gaia DR2 parallaxes. This group has clear counterparts both in (Kuhn et al. 2019) and in (Damiani 2018).

Group C
This is a very poor group located in the south west corner of the field we covered. It is essentially composed by early type stars (early B spectral type, judging from the colour-colour diagram), and therefore it shares the same age as Trumpler 24 (group B). The kinematic data support this association.

Group D
In spite of its vicinity to the previous group C, this group appears to be totally different. It does not contain young stars, and its kinematics is closer to VdB-Hagen 202 than to Trumpler 24. It seems also to be located somewhat in the background with respect to Trumpler 24. We suggest that this group is a part of the group A (see Table 5).

Group E
If we adopt the astrometric distance, this poorly populated group shares the same kinematics as group D, and lies very close to VdB-Hagen 202. Its paucity of stars prevents us from computing precise age. However, it seems plausible to adopt an age close to group D. We suggest that this group is a part of the group A (see Table 5).

Group F
This group shares the same properties of group C. It coincides with (Kuhn et al. 2019) group 3. A few early type stars, and age, kinematics and distance consistent with Trumpler 24.

Group G
This corresponds to Seggewiss (1968) group Trumpler 24 II. Similar to the C and F groups, this group is young. Even if it is situated right to the north of the old A group (VdB-Hagen 2020), it possesses mean proper motion components close to Trumpler 24.

Overall, this analysis of the detected group leads us to separate them in two families:

*family I*: B, C, F and G groups have colour-colour diagrams typical of a very young population, and show the presence of pre Main Sequence stars in the colour-magnitude diagram. They share similar proper motion components: \( \mu_\alpha^* = \mu_\alpha \cos \delta = -0.3 \text{ mas year}^{-1}, \mu_\delta = -1.3 \text{ mas year}^{-1} \).

*family II*: A, D and (maybe) E groups are significantly older and have compatible proper motion components: \( \mu_\alpha^* = -1.7 \text{ mas year}^{-1}, \mu_\delta = -3.7 \text{ mas year}^{-1} \). They have distances on average larger than family I.

### 4 PRE MAIN SEQUENCE STARS

(Eggen 1976) firstly suggested that a violent episode may have taken place in Sco OB1 association, which rich in pre Main Sequence (PMS) stars. (Heske & Wendker 1984)

Table 5. Physical parameters of groups from Gaia data

| Group | \( \alpha \) deg | \( \delta \) deg | Distance pc | \( \mu_\alpha^* \) mas year\(^{-1} \) | \( \sigma_\mu_\alpha^* \) mas year\(^{-1} \) | \( \mu_\delta \) mas year\(^{-1} \) | \( \sigma_\mu_\delta \) mas year\(^{-1} \) | \( v_T \) km s\(^{-1} \) | \( \sigma v_T \) km s\(^{-1} \) |
|-------|------------|------------|-------------|--------------------------|-----------------|--------------------------|-----------------|-------------|-----------------|
| A     | 253.781    | -40.956    | 1631\(^{+23}_{-19} \) | 1.86                      | 0.01             | -3.81                     | 0.01             | 33.46       | 0.81            |
| B1    | 254.042    | -40.677    | 1540\(^{+28}_{-20} \) | -0.22                     | 0.03             | -1.22                     | 0.03             | 9.25        | 0.59            |
| B2    | 254.141    | -40.571    | 1610\(^{+31}_{-28} \) | -0.07                     | 0.04             | -1.05                     | 0.03             | 8.11        | 0.29            |
| B3    | 254.199    | -40.635    | 1569\(^{+31}_{-23} \) | 0.04                      | 0.04             | -1.19                     | 0.03             | 8.95        | 0.5             |
| C     | 253.510    | -41.128    | 1521\(^{+20}_{-20} \) | -0.50                     | 0.07             | -1.72                     | 0.05             | 13.08       | 0.55            |
| D     | 253.571    | -41.120    | 1729\(^{+26}_{-27} \) | -1.80                     | 0.04             | -3.76                     | 0.03             | 34.07       | 0.8             |
| E     | 253.722    | -41.103    | 1663\(^{+30}_{-29} \) | -1.72                     | 0.12             | -3.75                     | 0.05             | 32.54       | 1.06            |
| F     | 253.606    | -41.041    | 1592\(^{+19}_{-16} \) | -0.41                     | 0.08             | -1.45                     | 0.11             | 11.42       | 0.88            |
| G     | 253.701    | -40.765    | 1533\(^{+20}_{-19} \) | -0.30                     | 0.03             | -1.31                     | 0.02             | 9.82        | 0.49            |
Table 6. Coordinates of objects and labels of the groups/clusters in the region according to SIMBAD and their properties according to Dias et al. (2002).

| Cluster          | Nearest group | α deg | δ deg | Distance pc | log(Age) dex | μα* mas year⁻¹ | σμα* mas year⁻¹ | μδ mas year⁻¹ | σμδ mas year⁻¹ |
|------------------|---------------|-------|-------|-------------|--------------|----------------|----------------|---------------|---------------|
| C 1652-405       | B1            | 254.046 | -40.667 | 2160        | 7.12         | -1.72          | 0.18            | -2.44         | 0.08          |
| ESO 332-11       | B2            | 254.025 | -40.780 | 1841        | 7.10         | -5.28          | 0.60            | 0.86          | 0.53          |
| ESO 332-13       |               | 254.166 | -40.575 | 2910        | 6.82         | -2.73          | 0.05            | -0.57         | 0.02          |
| C 1652-407       |               | 253.875 | -40.833 | 1000        |              | -              |                 | -0.89         | 0.54          |
| Trumpler 24      |               | 254.250 | -40.667 | 1138        | 6.92         | -4.36          | 0.03            | -0.17         | 0.04          |
| ESO 332-8 G      | G             | 253.680 | -40.708 | 1200        | 8.17         | -3.87          | 0.12            | -0.52         | 0.16          |
| VdB-Hagen 202 A  |               | 253.795 | -40.940 | 1607        | 8.05         | -2.55          | 0.21            | -2.89         | 0.33          |

Figure 6. WISE two colour diagrams of detected PMS in the surveyed area. Colours refer to detected groups as in previous figures, while in black we refer to stars not associated with detected groups.

found a large number of PMS star candidates in some portions of ScoOB1 in the V range from 11 to 14 mag. More recently, (Damiani 2018) performed an extensive search of such stars in X-rays, in Hα, and in infrared. Our study using deeper photometry, confirms the presence of these objects. In fact the CMDs of groups B, C, F and G (see appendix B) indicate the clear presence of stars in the region where PMS are expected to be. These star are members of the groups according to our criteria. To further check their nature we make use of photometry in mid-infrared from WISE (Cutri & et al. 2012), and cross-correlate it with our data-set. It is well known that PMS stars which have not lost circum-stellar disks completely exhibit an excess of emission in IR wavelengths (λ ≥ 2μ). To probe this, we closely followed the procedure described by Koenig et al. (2012). PMS stars are divided in three classes: Class III objects refer to PMS stars without disks (and also background stars, which we should not have in our sample), while Class II and I are young stellar objects with contracting envelopes and hence optically thick disks. They are separated by different amount of infra-red excess. Class I objects possess the highest infra-red excess, while Class II objects are intermediate. The separation is performed using the colour-colour diagrams [4.6]−[12] vs. [3.4]−[4.6], where [3.4],[4.6],[12] are the WISE (Cutri & et al. 2012) filters W1, W2, W3, correspondingly. There are also young objects which do not have excess emission at these wavelengths, but only beyond 20 μm, and they could be detected with the use of the colour-colour diagram [4.6]−[22] vs. [3.4]−[4.6], where [22] refers to W4 WISE filter. These objects are supposed to be so-called transition disks (TD), which may be the result of planet formation, photo-evaporation, or other processes that led to the disappearance of the inner disk.

In detail, we extracted data from WISE for stars in groups...
B, C, F, and G adopting a crossmatch radius of 2′′. We then considered only stars with photometry in filters W1, W2, W3 and W4. The results are illustrated in Fig. 7, and can be summarised as follow:

- **subgroup B1**: we identified 11 TD;
- **subgroup B2**: we found 13 TD and 3 Class II objects;
- **subgroup B3**: 15 TD are detected;
- **group C**: we identified 3 TD;
- **group F**: only 1 TD was found;
- **group G**: we identified 11 TD.

Then, by using the same scanning criteria, we looked for PMS stars that are not associated with our groups of family I, but that share the same kinematics and distance. We found 158 stars (indicated in black in Fig. 6), 136 of which are TD, and 22 Class II objects. Their spatial distribution is shown in Fig. 7.

Therefore, we found PMS stars everywhere in the area we have surveyed, down to V = 18 mag. This population of scattered PMS stars are therefore members of family I. The whole family would then correspond to the very same Star Formation event whose outcome appears to have a complicated spatial structure, with different degrees of concentration across the association.

As shown in Figs 10 and 11 in (Damiani 2018) the highest concentration of young objects of M-types in his work coincides with the locus occupied by our groups B, A, C, F, G and D (although group G is a bit displaced to the north-west).

According to (Damiani 2018) the visual absorption \( A_V \) in Sco OB1 steadily decreases moving from NGC 6231 toward Trumpler 24. If we adopt the widely accepted value \( A_V = 1.29 \) (E(B-V) =0.43) for NGC 6231 and include it together with the respective values determined for the seven groups in Table 4, the absorption increases from NGC 6231 to groups C, D, E, and A. Group F, slightly to the est of group A, shows an absorption value quite close to the one of NGC 6231. Immediately north of group A, group G appears showing the lowest absorption value (\( A_V = 1 \)) in the surveyed region. The remaining three subgroups B1, B2, and B3 show, in turn, small \( A_V \) values, close to the one of NGC 6231. Therefore we can confirm (Damiani 2018) result in the sense that Tr 24-S is more affected by visual absorption than Tr 24, but we notice as well that NGC 6231 is less reddened than Tr 24-S.

The spatial distribution of family I stars (both OB and pre MS stars) is shown in Fig 7. The density map in the lower panel shows how all PMS stars in family I increase in concentration toward Tr 24 (group B). The upper panel containing all PMS stars found in the area confirms the trend that has been also reported in Damiani (2018) this is, 

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UV excess and N3 emission stars increase in number from Tr 24-S toward Tr 24 and IC 4628 exactly as our PMS stars do. Following upper panel in Fig. 7, it is seen an evident downfall in the density number of PMS stars north east of Tr 24. However, density numbers in this figure should be taken with care: the region north of Tr 24 is dominated by the HII region G345.45+1.50 whose brightness prevent us to get deeper observations in our UBVI photometry. So, we see that despite the reddening is constantly decreasing toward the north part and therefore we could in principle detect more, fainter, stars, the brightness of the nebula becomes higher thus reducing this advantage. We are confident this a reasonable argument to explain why many low mass stars (at larger magnitudes) may have not been detected in our passband.

We finally draw our attention to the CMD of family I stars with a zoom on the PMS stars region, which is shown in Fig. 8. Super-imposed are stellar isochrones from the Padova suite of models (Marigo et al. 2017) for the labelled ages. We indicate also a few representative value of the stellar masses, as extracted from the isochrones. We can notice that PMS stars in this area of Sco OB1 have a mass range from 0.5 to 3 \( M_\odot \).
The young rich open star cluster NGC 6231 is situated in the close vicinity of the area under investigation and has been a target of intense study in the past (Reipurth 2008). The logAge is supposed to be about 6.3 - 6.9 dex (Damiani et al. 2016; Sung et al. 2013). As for distances, Reipurth (2008) noted that the mean estimation of distance is 1.6 kpc. Dias et al. (2002) listed the distance of 1243 pc, which seems to be underestimated. Kuhn et al. (2019) found the distance of 1710 pc from Gaia DR2 parallaxes. We adopted here distance to NGC 6231 equals 1585 pc, given by Sung et al. (2013), which is widely accepted (Damiani 2018).

The age of NGC 6231 is in good agreement with the ages of family I groups. We adopted proper motion $\mu_\alpha = -0.55 \pm 0.07$ mas year$^{-1}$, $\mu_\delta = -2.17 \pm 0.07$ mas year$^{-1}$ from Kuhn et al. (2019) and plot it with the mean proper motion values of the groups (Fig. 5). Again, its value is close to the estimations for the family I.

Thus, groups from sample I have roughly the same distances and age of NGC 6231 and share similar kinematics. They all are very young, approximately the same age as NGC 6231. These facts leads us to the idea of the connection of star formation histories of family I groups and NGC 6231.

In conclusion, family I is a stellar population associated with the association whose centre is NGC 6231, while family II is an older population which is not related to the association.

With the third release of Gaia data, which is expected to be in the second half of 2021, it will be possible to get a better understanding of processes of this region. With the knowledge of radial velocities one will have the opportunity to trace orbits of objects of interest back in time, and estimate the most probable time and place of formation.

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APPENDIX A: COLOR-COLOR DIAGRAMS
APPENDIX B: COLOR-MAGNITUDE DIAGRAMS

This paper has been typeset from a \TeX/\LaTeX file prepared by the author.
Figure A1. Color-color diagrams of groups. Red and black lines are intrinsic and shifted ZAMS.
Figure B1. Color-magnitude diagrams of groups. Black dashed lines are shifted ZAMS. Solid lines are shifted isochrones. For groups D and E ages were estimated by brightest stars.