Comparing the spatial and kinematic distribution of gas and young stars around the shell-like structure in the CMa OB1 association

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ABSTRACT

Context. The relationship between young stellar clusters and their respective parental molecular clouds remains an open issue. Recent inquiries consider the similarities between substructures of clouds and clusters and whether they are a coincidence or, rather, an indication of a physical relationship. To address these issues, we studied the CMa OB1/R1 region, which shows evidence of a complex star formation history.

Aims. We obtained molecular cloud mapping with the IRAM-30 metre telescope to reveal the physical conditions of an unexplored side of the CMa region with the aim of comparing the morphology of the clouds to the distribution of young stellar objects (YSOs). We also studied the cloud kinematics in pursuit of gradients and jet signatures that could trace different star formation scenarios.

Methods. The YSOs were selected on the basis of astrometric data from Gaia EDR3 that characterize the moving groups. The distance of 1099.249 pc was obtained for the sample, based on the mean error-weighted parallax. Optical and near-infrared photometry was used to verify the evolutionary status and circumstellar characteristics of the YSOs.

Results. Among the selected candidates, we found 40 members associated with the cloud: 1 Class I, 11 Class II, and 28 Class III objects. Comparing the spatial distribution of the stellar population with the cores revealed by the 12CO map, we verified that peaks of emission coincide with the position of YSOs, confirming the association of these objects to their dense natal gas.

Conclusions. Our observations support the large-scale scenario of the CMa shell-like structure formation as a relic of successive supernova events.

Key words. stars: pre-main sequence – circumstellar matter – ISM: individual objects: CMa OB1 – ISM: clouds – ISM: kinematics and dynamics – infrared: stars

1. Introduction

It is clear that OB associations are ideal sites for testing our understanding of star formation and how this process is influenced by the feedback from massive stars. The interplay between supernova (SN) events and the star-forming molecular cloud is of key relevance to the star formation process, as shown in several examples from the literature. In particular, it has been proposed that SN are able to affect star formation negatively by suppressing the formation of new stars in their surroundings, as well as positively by triggering it (see review by Hensler et al. 2011). In the latter case, the expansion of SN remnant (SNR) shells can sweep up the surrounding gas up to the point of triggering sequential star formation (according to the “collect and collapse” model of Elmegreen & Lada 1977).

The extended HII region Sh 2-235, for instance, is an active star-forming region where star formation triggered by a SN appears to have occurred in two nebulae: S235A and S235B (Kirsanova et al. 2014). The young stars associated with both nebulae are ~0.3 Myr old, coinciding with the age of the SNR proposed by Kang et al. (2012). Another interesting example is W28 SNR (Lefloch et al. 2008; Vaupré et al. 2014), whose interaction with nearby molecular clouds could have triggered the formation of nearby protostellar clusters in the Trifid nebula. In the case of the SNR IC443, however, despite the fact that many young stellar objects (YSOs) are found surrounding the SNR shell, the SNR proved to be too young as compared to the age of YSOs and could not have triggered their formation (Xu et al. 2011). Recent numerical simulations by Dale et al. (2015) have been able to reproduce triggering of star formation. However, when making comparisons with observations, the authors found that triggered star formation is much harder to infer since they could not discriminate triggered from non-triggered objects.

Star formation is, in any case, often found in the vicinity of SNRs; for instance, there are several SNRs associated with YSOs in the Large Magellanic Cloud (e.g. Desai et al. 2010), and it has long been suggested that supernovae have the ability to excite star formation in their surrounding regions. The arc-shaped
Sh 2-296 nebula is one of these cases, suspected to be an old SNR that might have triggered the formation of new stars in CMa OB1 (Herbst & Assousa 1977).

The Canis Major OB1/R1 (henceforth CMa, for simplicity) is a nearby ($d \sim 1$ kpc) OB Association with a complex star formation history. Our previous studies have shown that the region contains young objects originating from different star-forming events (Gregorio-Hetem et al. 2009; Santos-Silva et al. 2018).

A promising hypothesis has been presented by Fernandes et al. (2019), demonstrating new evidence that Sh 2-296, the most prominent nebula in the CMa association, is part of a large (i.e., diameter of $\sim 60$ pc) shell-like structure. Figure 1 shows this structure, called the CMa “shell”, which is likely to have resulted from successive SN explosions from 6 to 1 Myr ago, as inferred from the past trajectories of three runaway stars in the region that were derived from Gaia proper motions. They also found evidence that the CMa shell is related to a larger ($\sim 140$ pc in size) shell structure, visible in Hα. However, the older population of low-mass stars ($\geq 10$ Myr), which are confirmed CMa members, cannot be explained by these recent SN explosions, suggesting that they may be causally related to the existence of the Hα super-shell.

Fernandes et al. (2019) suggest that the present-day configuration of the star-forming gas may have been shaped by a few successive SN explosions that occurred several Myr in the past. Despite the evidence of SN events shaping the CMa shell, Fernandes et al. (2019) argue that they probably played a minor role in triggering star formation in these clouds. Thus, CMa may serve an ideal laboratory for probing how the feedback from SNRs interacting with molecular clouds can affect their environment as well as the subsequent star formation and evolution in OB associations.

2. Molecular clouds in CMa

A $^{13}$CO ($J = 1$–$0$) survey of Kim et al. (2004), using the Nagoya-4m telescope with a beam width of 2.7, identified 13 molecular clouds in the area of the CMa Association, distributed across three main structures around the clouds No. 3 ($l \sim 224^\circ$, $b \sim -2^\circ$), No. 4 ($l \sim 224^\circ.5$, $b \sim -1^\circ$), and No. 12 ($l \sim 226^\circ$, $b \sim -0.5^\circ$).

Partial maps of these molecular clouds were recently obtained with the 1.85 m mm-submm Telescope installed at the Nobeyama Radio Observatory1. According to Onishi et al. (2013), the 1.85 m telescope is dedicated to a large-scale survey

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1 As courtesy of the Osaka Prefecture University group, a $^{13}$CO map of the CMa region was obtained by T. Onishi & K. Tokuda (priv. comm.).
Fig. 2. DSS2-Red image of the Sh 2-296 nebula. The ellipses mark the proposed shape of the CMa shell and the contours in each panel trace: (a) the 13CO emission (courtesy of the Osaka group, see Onishi et al. 2013); (b) extinction ($A_v$) from the 2MASS maps of Dobashi et al. (2011). The figure is adapted from Fernandes et al. (2019).

aiming to reveal the physical properties of molecular clouds in the Milky Way Galaxy. In the 1.3 mm band, observations of the rotational transition $J = 2–1$ of $^{13}$CO, $^{13}$CO and $^{18}$O were obtained, with a beam size of 2.7.

The $^{13}$CO map shows a chain of molecular clouds that extends north-east of the Sh 2-296 nebula. In Fig. 2a, the main structure associated with Sh 2-296 is referred to as the “west cloud”, which coincides with “Cloud 3” of the list from Kim et al. (2004). This is the largest cloud of the region, with a mass of $\sim 16000 M_\odot$ and an area of $358$ pc$^2$. To the north-east, the second main structure, called the “east cloud”, is related to “Cloud 4” (total mass $\sim 12000 M_\odot$ and area $\sim 301$ pc$^2$).

The clouds are also traced by the dust distribution revealed by the extinction map of $A_v$ (Fig. 2b) from Dobashi et al. (2011). We can see that the dust emission closely matches the $^{13}$CO distribution, following the approximate shape of the CMa shell. Comparing Figs. 2a,b, we note that there is a lack of information on the $^{13}$CO emission for “Cloud 12”, which is found in the area not covered in the survey obtained by the Osaka group (see the dashed rectangle in Fig. 2a). This cloud is the third-largest gas reservoir in the CMa association, with an estimated mass of $7500 M_\odot$ and an area of $315$ pc$^2$ (Kim et al. 2004). Besides the significant amount of gas it holds, this cloud is located in the border of the CMa Shell, on the opposite side of Sh 2-296 nebula.

This work is dedicated to an investigation of this complementary area of gas distribution, which can bring an important contribution to the general understanding of the star formation scenario in CMa. In the general context, we aim to explore the global dynamics that allows us to search for signatures of the large-scale SNR-driven shock and its interaction with the molecular gas condensation. In Sect. 3, we summarize the surveys used in the analysis and the molecular gas observations. The identification and analysis of young stars associated with the cloud are presented in Sect. 4. Finally, in Sect. 5, we discuss the results from the molecular cloud mapping in comparison to the characteristics of the associated stellar population. The conclusions are summarized in Sect. 6.

3. Observational data

3.1. Dust continuum surveys

Besides the visual extinction map that is compared to the molecular cloud distribution in Sect. 2, here we analyze the dust distribution traced by the infrared emission. We are particularly interested in the search for condensations and filamentary structures that is aimed at verifying whether they are harbouring prestellar cores, as suggested by Elia et al. (2013).

As part of the Herschel Infrared Galactic plane survey (Hi-GAL Molinari et al. 2010), Elia et al. (2013) conducted a study of star formation in the third Galactic quadrant, which includes the CMa region. In this study, Herschel PACS and SPIRE$^2$ photometric observations were combined with NANTEN CO $J=1–0$ observations of cores and clumps, revealing that most of the protostars are in the early accretion phase, while star formation is still underway in cores distributed along filaments.

The filamentary structure of “Cloud 12” studied here can be clearly seen in the Herschel SPIRE map obtained at 250 $\mu$m, which is shown in Fig. 3 (left panel). The position of bright infrared sources (flux density $> 3$ Jy at 100 $\mu$m band) from the IRAS Catalogue of Point Sources (Helou & Walker 1988) is also plotted in this figure, showing a good correlation with the bright filaments.

We also performed the characterization of the infrared (IR) sources associated with the clouds by searching for candidates in the AllWISE catalogue (Cutri et al. 2013). The WISE photometry (Wright et al. 2010) at bands W1 (3.4 $\mu$m), W2 (4.6 $\mu$m), and W3 (12 $\mu$m) are useful for distinguishing among different classes of YSOs as a function of their IR excess.

As shown in Fig. 1, the CMa clouds contain several groups of YSO candidates identified by Fischer et al. (2016) based on WISE colors. The candidates were selected by adopting the criteria proposed by Koenig & Leisawitz (2014) to identify Class I and Class II objects. Details on this method, which we also apply here, is presented in Sect. 4.2.1. The distribution of the groups of YSOs found by Fischer et al. (2016) closely follows the border of the CMa Shell and coincides with the gas distribution.

3.2. Molecular gas

In order to characterize the properties of the cores and filaments associated with star formation activity, as revealed in the AllWISE and Herschel surveys, we used the IRAM-30 m telescope (Sierra Nevada, Spain) to map the emission of the ground-state...
Table 1. Observational properties of a sample of molecular cores.

| Core | $\Delta \alpha$ (arcsec) | $\Delta \delta$ (arcsec) | RA (J2000) (h m s) | Dec (J2000) (° ′ ″) | $T_{\text{kin}}$ (K) | $N^{(13}\text{CO})$ (10^{16} cm^{-2}) | $N^{(\text{H}_2})$ (10^{22} cm^{-2}) | Outflow | Comment |
|------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|---------|---------|
| 1    | −325            | 165             | 07 13 30        | −12 16 43       | 8               | 3.3             | 2.1             | Y       |         |
| 2    | −285            | 130             | 07 13 33        | −12 17 18       | 8               | 3.3             | 2.1             | N       |         |
| 3    | 375             | 180             | 07 14 17        | −12 16 28       | 13              | 5.0             | 3.3             | Y       | Broad wings |
| 4    | 395             | 245             | 07 14 18        | −12 15 23       | 13              | 3.5             | 2.3             | Y       | Broad wings |
| 5    | 390             | 550             | 07 14 18        | −12 10 18       | 10              | 3.8             | 2.5             | Y       | Broad wings |
| 6    | 490             | 740             | 07 14 25        | −12 07 08       | 12              | 1.2             | 0.8             | Y       | Small wings |
| 7    | 520             | 915             | 07 14 27        | −12 04 13       | 12              | 0.7             | 0.5             | Y       | Blueshifted wing |
| 8    | 550             | 1250            | 07 14 29        | −11 58 38       | 7               | 0.7             | 0.5             | N       |         |
| 9    | 615             | 1605            | 07 14 33        | −11 52 43       | 9.5             | 1.2             | 0.8             | N       |         |

Notes. The physical parameters: kinetic temperature ($T_{\text{kin}}$), and column density ($N^{(13}\text{CO})$) were obtained from averaging the signal over a region of $20'' \times 20''$. A value $T_{\text{kin}} = 10$ K was adopted for Core 5 due to the lack of detection of C^{18}O.

The pointing was monitored every hour on a nearby quasar and corrections were always found lower than $3''$. Special attention was paid to the line calibration and we obtained a very good agreement among the different runs. The calibration uncertainty is about 10% in the 3 mm band.

The data reduction was performed using the GILDAS software developed at IRAM. The line intensities are expressed in units of antenna temperature corrected for atmospheric attenuation and rearward losses ($T_A^*$. For the subsequent radiative transfer analysis of the pre- and protostellar core emission, line fluxes were expressed in units of main beam temperature ($T_{\text{MB}}$). The main beam efficiency and the half power beam width (HPBW) were taken from the IRAM webpage.

3 http://www.iram.fr/IRAMFR/GILDAS/

4 http://publicwiki.iram.es/Iram30mEfficiencies
The right panel of Fig. 3 illustrates the pre- and protostellar condensations that were detected thanks to the IRAM-30 m angular resolution. Table 1 gives the results for a sample of molecular cores shown in Fig. 3 (middle panel).

### 4. Stellar population

Two groups of YSOs (Fischer et al. 2016) are projected onto the eastern border of the CMa shell, coinciding with the location of the “Cloud 12” identified by Kim et al. (2004). Our preliminary analysis on the distribution of YSO candidates (selected from the AllWISE catalogue) is well correlated with the dust distribution revealed by the λF map in a 800 arcmin² area within the cloud (Fig. 2).

Here, we extracted optical and infrared data (public catalogues) for stars found in the direction of the fields observed with IRAM-30m, searching for candidates that are likely to be members associated with the cloud (Sect. 4.1). The selected members are then characterized on the basis of infrared colors that allow us to identify Classes I and II objects (Sect. 4.2.1). The confirmation of the pre-main sequence nature of the candidates is obtained from a color-magnitude diagram using Gaia EDR3 photometry (Sect. 4.2.2).

#### 4.1. Selection of members

With the aim of excluding the presence of field-stars in the sample, as well as confirming the membership of the objects associated with the cloud, we performed a selection of kinematic members by using the techniques described by Hetem & Gregorio-Hetem (2019). Following the formalism presented by Dias et al. (2014), the adopted statistical methods use likelihood model and cross entropy technique to estimate the probability of a candidate to be (or not to be) considered a cluster member. A vector of parameters consisting of astrometric and kinematic data given by the observed proper motion is used to calculate the probability density function for a candidate and for the background of field-stars. The membership probability basically results from the fitting of a Gaussian in 5D phase space (three positions and two components of proper motion) by comparison with the Gaussian background. Since the cross entropy is sensitive to the initial parameters, a genetic algorithm code is adopted for parameters optimization (Hetem & Gregorio-Hetem 2019).

The first subset of candidates was obtained by querying astrometric and kinematic data from the Gaia EDR3 catalogue (Gaia Collaboration 2016b, 2020a). The search was performed in an area slightly larger than the fields observed with IRAM-30m. We also delimited the query in ranges of parallax and proper motion compatible with results previously found for CMa (e.g. Santos-Silva et al. 2021). According to the Gaia technical recommendations, we applied the RUWE (Re-normalized unit weight error (see details in the technical note GAIA-C3-TN-LU-LL-124-01)) selection filters in order to avoid any low quality with regard to the astrometric solution.

Table 2 gives the intervals of parameters adopted for the catalogue query, as well as the results found for our sample. The mean values obtained for proper motion define the membership criteria. An illustration of the reliability of the method is given in Fig. 4 (left panel), where the distribution of probabilities is presented as a function of a modulus of proper motion \( |\mu| = (|\mu_\alpha|^2 + |\mu_\delta|^2)^{1/2} \). We suggest that objects with membership probability \( P \geq 50\% \) are very likely associated with the ambient cloud, which are considered very likely CMa members here. These members have a value of \((\mu_\alpha, \mu_\delta)\) that is within 1σ of the mean values found for the sample. Objects appearing below the dashed line (\( P < 50\% \)) are selected candidates of field stars, since they have proper motion parameters in ranges that are larger than the 1σ threshold adopted by us.

Santos-Silva et al. (2021) use HDBScan technique to fit five parameters from Gaia aiming to explore the stellar clusters and sub-groups in the entire CMa region. No sub-group was found by them in the area studied here, probably due to the low number of members, or the objects are too faint to be identified by the automatic procedure. However, it is interesting to compare our results with those found by Santos-Silva et al. (2021) for the group they call “CMa06”, which coincides with the Sh 2-296 nebula (see the “west cloud” in Fig. 2a). Despite the fact that this cluster is located on the opposite side of the CMa shell (\( \sim 2\degree \) to the W), its parallax and proper motion are quite similar to the results of our sample. This may be due to a common star formation history. A similar result was independently achieved by Gregorio-Hetem et al. (2021) in the study of objects associated with Sh 2-296 using the same method adopted here (Hetem & Gregorio-Hetem 2019), which validates our criteria with regard to the selection of cloud members. The results found for CMa06 and Sh 2-296 are also presented in Table 2.

In order to evaluate the error-weighted parallax, we adopted the calculation used by Navarrete et al. (2019), based on the uncertainty on the measured parallax \( \sigma_\pi \) and the spatial correlation between the position of the sources. We obtained for our sample the mean parallax \( \bar{\pi} = 0.91 \pm 0.02 \) mas that was converted to the distance of 1099 ± 25 pc. Figure 4 (right panel) shows the distribution of parallaxes and error bars given in Table A.1, highlighting 11 stars (2 Class II and 9 Class III) that coincide with the secondary structure of the cloud found in the centre of the gas distribution, as discussed in Sect. 5.

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**Table 2.** Limits used for the Gaia data query and results from the kinematic members selection.

| ID     | RA (J2000) | Dec (J2000) | \( \sigma \) (mas) | \( \mu_\alpha \) (mas yr\(^{-1}\)) | \( \mu_\delta \) (mas yr\(^{-1}\)) |
|--------|------------|-------------|--------------------|----------------------------------|----------------------------------|
| Query range | 07h13m to 07h15m | -12°35' to -11°45' | 0.4 to 2 | -7 to 1 | -4 to 4 |
| \( P \geq 50\% \) | 07h13m to 07h14m, 4 | -12°14' to -11°58' | 0.87 ± 0.30 | -3.26 ± 0.44 | 1.08 ± 0.46 |
| CMa06    | 07h03m to 07h05m, 6 | -11°34' to -11°00' | 0.85 ± 0.09 | -4.18 ± 0.36 | 1.52 ± 0.21 |
| Sh 2-296 | 07h01m to 07h06m, 8 | -12°12' to -10°48' | 0.8 to 1.25 | -4.10 ± 0.60 | 1.50 ± 0.40 |

**Notes.** Our sample \( (P \geq 50\%) \) is compared with clusters CMa06 (Santos-Silva et al. 2021) and Sh 2-296 (Gregorio-Hetem et al. 2021) located to the W direction of the CMa shell.

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5. http://www.rssd.esa.int/doc_fetch.php?id=3757412

6. Re-Normalized unit weight error (see details in the technical note GAIA-C3-TN-LU-LL-124-01).
4.2. Characterization

4.2.1. Infrared excess

The IR data from AllWISE catalogue were used for two purposes: (i) characterizing the stars that were selected as members of CMa on the basis of proper motion; and (ii) searching for embedded sources that were not detected by *Gaia*, likely due to high levels of extinction in dense regions. The query was restricted to the same area described in Sect. 4.1.

Our analysis of IR-excess is based on color-color diagrams using WISE bands: W1 (3.4 μm), W2 (4.6 μm), and W3 (12 μm) that are useful to distinguish different classes of pre-main sequence stars. Based on the results from Rebull et al. (2014) for the Taurus star-forming region, Koenig & Leisawitz (2014) proposed limits on the [W1 − W2] × [W2 − W3] diagram defining the expected locus for Class I and Class II objects due to their significant IR-excess compared with Class III objects and field-stars.

In order to ensure the photometric quality, we extracted from the AllWISE catalogue only the sources that are in agreement with the following conditions for the magnitude measured at 12 μm: 0.45 < W3 amat < 1.15 and W3 amat > 5, where r2 and SNR correspond to the photometric error and signal-to-noise ratio (S/N), respectively. According to Koenig & Leisawitz (2014), these filters are applied with the purpose of mitigating any contamination from fake detections.

Figure 5 displays the [W1 − W2] × [W2 − W3] diagram for 383 sources that coincide with the fields observed with IRAM-30m and that are common on both catalogues: *Gaia* and WISE, which membership probability is represented by different symbols. It can be noted that most of the studied objects (89%) are plotted in the region where Class III or field-stars are expected to be found.

Our final sample contains 40 members (1 is Class I; 11 are Class II; and 28 are Class III) confirmed by proper motion (P ≥ 50%), and 4 candidates (1 is Class I, and 3 are Class II). Since we are mainly interested in embedded objects, Class III candidates (P < 50%) were not included in the sample. Table A.1 gives the list of objects and the *Gaia* EDR3 parameters used in the membership probability calculation. The division between the classes of objects is indicated by double-lines in Table A.1.

With the aim of complementing the list of objects, we also searched for WISE sources that were not detected by *Gaia*. Due to the lack of membership information for these additional sources, only Class I or Class II objects are considered by us as possible members. In other words, among the WISE candidates not detected by *Gaia*, Class III objects were not taken into account due to the difficult in distinguishing them from field stars. In this way, the sample is complemented by 45 WISE sources that we consider possible members (12 are Class I and 33 are Class II). The distribution of the sources in the equatorial coordinates space is shown in Fig. 6 (left panel). The IR photometry used in the analysis of the stellar population is given in Table A.2 for the same list presented in Table A.1.

For our sample, we verified the presence of Hα emitters by using a cross-correlation with the results from Pettersson & Reipurth (2014) that revealed 353 new Hα stars in the direction of CMa. The area surveyed by us contains ten Hα stars. However, only four of them coincide with the CMa members, meaning that the other Hα stars have proper motion or parallax in disagreement with the kinematic selection criteria adopted by us. In Table A.1, we added a comment marking each of the Hα stars as identified by Pettersson & Reipurth (2014), which are classified by us as Class II objects. For classical T Tauri stars, the Hα emission is an evidence of accretion process that is expected for Class II objects and is also related to the presence of a circumstellar disk. The characteristics of these four Hα stars are in agreement with their young age (<5 Myr), which is estimated in the next section.

4.2.2. Cluster age

In order to confirm the youth of the sample, we constructed a color-magnitude diagram using the photometric data at bands G (∼600 nm), Grp (∼500 nm), and Grp (∼700 nm) from *Gaia* EDR3. The magnitudes were corrected for reddening by adopting the Aν/AV relations from Cardelli et al. (1989). For each source, we calculated the distance modulus given by its parallax, which was used to estimate the unreddened absolute magnitude (M_G).
M have colors similar to those we do not find any massive stars. The brightest Class III objects are not affected by circumstellar IR-excess, we arguing that this low level of A_V corresponds to the interstellar reddening in the direction of CMa, which is in agreement with the extinction map of the region (Gregorio-Hetem et al. 2008). We conclude that it is highly probable that the Class III stars are observed in the near vicinity, but are preferentially located in the foreground of the cloud.

The same can be said for other sources detected by Gaia, since they are visible. However, some of them are too faint ([M_B] > 8 mag in right panel of Fig. 6), probably due to a reddening that needs to be corrected with a higher value of A_V, which should be evaluated individually. This can be the case of sources that are still surrounded by some amount of cloud material.

We are aware that the use of optical color-magnitude diagrams gives only a rough estimation of age. Despite this, it can still be noted that most of the sources exhibiting IR excess (Class I and Class II) are ~5 Myr or younger. Several of the Class III objects presented here are in the same range of age and a few sources seem to be older, but still in the pre-main sequence phase, confirming the youth of our sample. Among the Gaia EDR3 sources, we do not find any massive stars. The brightest Class III objects have colors similar to those 2 M5 stars.

As mentioned in Sect. 4.1 the proper motion of our sample, which is located in the east side of the CMa shell, coincides with the values found for group CMa06 located to the west. The estimated age for this group is 6 ± 1 Myr (Santos-Silva et al. 2021).

Figure 6 (right panel) shows the distribution of our sample in the (M_B) × [G_B-G_R] diagram compared with isochrones from PARSEC (Bressan et al. 2012; Marigo et al. 2017). The models for 1 and 5 Myr were adopted to indicate the range of ages previously reported for the CMa young population (Gregorio-Hetem et al. 2009), while the 100 Myr isochrone was chosen as representative of the zero-age main sequence (ZAMS).

In the color-magnitude diagram, we display only the sources with good photometric data, which show S/N > 10 in all bands. Some of the Class III objects show a good fit with the ZAMS, indicating that we adopted a suitable mean value of visual extinction (A_V = 0.9 mag) in the reddening correction. Since the Class III objects are not affected by circumstellar IR-excess, we argue that this low level of A_V corresponds to the interstellar reddening in the direction of CMa, which is in agreement with the extinction map of the region (Gregorio-Hetem et al. 2008). We conclude that it is highly probable that the Class III stars are observed in the near vicinity, but are preferentially located in the foreground of the cloud.

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Figure 6. Spatial distribution and color-magnitude diagram. Left: equatorial coordinates of Class I (filled symbols) and Class II (open symbols) that are CMa members (triangles) and additional candidates from AllWISE catalogue (circles). Right: absolute magnitude as a function of color from Gaia data for the CMa members (P ≥ 50%). The magnitudes are corrected for extinction. We use isochrones from PARSEC models, by adopting the 100 Myr line as representative of the ZAMS.

Figure 7. Mosaic of 13CO maps showing in each panel a different range of gas velocity, from 12.6 to 19.2 km s^{-1}. A main structure with V = 15 ± 1.2 km s^{-1} is clearly seen at RA ~ 07^h 14^m 5, growing from N to S and then continuing to SW. A secondary structure at V = 17.4 ± 1.2 km s^{-1} appears at the centre of the plot (RA = 07^h 14^m, Dec = 12° 10'). Despite their partial overlapping, they seem to be two structures representing different parts or movements of the cloud. The relative motions of these two gas structures are suggestive of a large-scale expanding gas motions around the cavity detected in the molecular gas at IRAM and in the continuum emission with SPIRE (see Fig. 3). It is remarkable that the "cavity" appears to be void of young stars and protostars.

5. Comparing gas and star distributions

As can be seen in Figs. 3 and 6, the projected spatial distribution of our sample of stars closely follows the filamentary structure present in the 13CO gas. Most of the Class II sources are found around dense cores, probably having emerged from the cloud and are still associated with it.

In Fig. 7, we plot a mosaic of 13CO maps showing in each panel a different range of gas velocity, from 12.6 to 19.2 km s^{-1}. A main structure with V = 15 ± 1.2 km s^{-1} is clearly seen at RA ~ 07^h 14^m 5, growing from N to S and then continuing to SW. A secondary structure at V = 17.4 ± 1.2 km s^{-1} appears at the centre of the plot (RA = 07^h 14^m, Dec = 12° 10'). Despite their partial overlapping, they seem to be two structures representing different parts or movements of the cloud. The relative motions of these two gas structures are suggestive of a large-scale expanding gas motions around the cavity detected in the molecular gas at IRAM and in the continuum emission with SPIRE (see Fig. 3). It is remarkable that the "cavity" appears to be void of young stars and protostars.

The presence of these two cloud structures and their connection with the stellar population was confirmed by analyzing the gas kinematics through moment maps similar to the works by Álvarez-Gutiérrez et al. (2021) and Stutz & Gould (2016),
profiles. We could check that the results are essentially independent of line-width (FWHM) measured from a Gaussian fit to the line velocity gradient approximation (Sobolev 1958, 1960), using the radiative transfer code MADEX (Cernicharo 2012) in the large-profiles and optical depths were subsequently modeled with the \( \tau \) depths ratio \\
\[
\frac{\tau}{n}
\]
the \(^{13}\)CO lines of cores 1, 3, 4, 5, 6, and 7 in Fig. 3. In the case of core 4, the outflow wings reach velocities as high as 20 km\( \cdot \)s\(^{-1} \) that is clear evidence for active, possibly massive, star formation in the core. Some of these cores (e.g., cores 6 and 7) are associated with IR (WISE) sources and we note that many of the IR sources coincide with the \(^{13}\)CO cores identified in our map. We speculate that the absence of IR sources in the other cores which display bipolar outflow signatures indicates that the driving protostars might be at earlier stage of evolution, possibly Class 0.

Conversely, other dense cores detected in our observations appear to be in a quiescent stage, as indicated by cores 2, 8, and 9 (Fig. 3). Based on our molecular gas content analysis (presented in Table 1), it appears that the cores in the northern part of the region (\( n \geq 6 \)) tend to have lower gas column densities. More work is needed to confirm this trend (higher densities found in the southern part of the cloud), based on a very reduced sample, and to investigate whether it is related to the physical or chemical evolution (depletion, perhaps) of the region.

Despite the fact that all the dense cores (kinetic temperatures from 10 to 14 K) are found in the main structure, with most of the stellar members associated with it, there are 1 Class I and 8 Class II sources located in the direction of the secondary, smaller cloud structure. Since only two of these stars are \( \textit{Gaia} \) sources, we cannot evaluate kinematic differences compared with the stars associated with the main structure.

Indeed, no trend is observed when comparing the spatial distribution of sources that have their proper motion vectors displayed in Fig. 8. The same can be said for the parallax distribution (see Fig. 4), where 9 Class III sources are also highlighted because they appear in the secondary structure, but without showing trends on \( \pi \). However, it is interesting to note that 2MASS07134800-1206336, found in the secondary structure, is the brightest star of the Class II objects (\( G_{\text{Gaia}} = 13 \) mag), which appears in the red side of the color-magnitude diagram (see Fig. 6, right panel), with an age of \(< 1 \) Myr. The parallax of this bright source indicates it is in the largest distance \( (\pi = 0.62 \pm 0.04) \), as compared with the other members. Therefore, it is possible that the reddening still needs to be corrected for this source and its mass is expected to be greater than 2 \( M_{\odot} \).

\section*{6. Conclusions}

In this study, we mapped molecular clouds with the IRAM-30 m to investigate the properties of cores and filaments to determine the spatial and kinematic distributions of gas in the cloud and their relation with the star formation activity. In the general context, we aim to search for and characterize the shock driven by the SN into the molecular cloud, which would be responsible for the gas compression and gravitational collapse.

Comparing the spatial distribution of the stellar population with the cores revealed by the \(^{13}\)CO map, we verify that peaks of emission coincide with the position of YSOs (see Fig. 3). These results confirm that CMa harbors pre- and protostellar cores showing that star formation is still underway in cores distributed of dark clouds and star-forming cores, namely, the ground state transitions are thermalized.

We adopted MADEX in this study to derive the kinetic temperature and the molecular gas column density in the cores. The main result is that these cores consist of cold gas, with temperatures in the range of 8–13 K. One of the most direct signs of protostellar activity is the signature of mass-loss phenomena (outflows) as broad wings in the CO rotational line profiles observed towards dense cores. This is illustrated in the CO lines profiles of cores 1, 3, 4, 5, 6, and 7 in Fig. 3. In the case of core 4, the outflow wings reach velocities as high as 20 km\( \cdot \)s\(^{-1} \) that is clear evidence for active, possibly massive, star formation in the core. Some of these cores (e.g., cores 6 and 7) are associated with IR (WISE) sources and we note that many of the IR sources coincide with the \(^{13}\)CO cores identified in our map. We speculate that the absence of IR sources in the other cores which display bipolar outflow signatures indicates that the driving protostars might be at earlier stage of evolution, possibly Class 0.

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In this study, we mapped molecular clouds with the IRAM-30 m to investigate the properties of cores and filaments to determine the spatial and kinematic distributions of gas in the cloud and their relation with the star formation activity. In the general context, we aim to search for and characterize the shock driven by the SN into the molecular cloud, which would be responsible for the gas compression and gravitational collapse.

Comparing the spatial distribution of the stellar population with the cores revealed by the \(^{13}\)CO map, we verify that peaks of emission coincide with the position of YSOs (see Fig. 3). These results confirm that CMa harbors pre- and protostellar cores showing that star formation is still underway in cores distributed of dark clouds and star-forming cores, namely, the ground state transitions are thermalized.
along filaments, as suggested by Elia et al. (2013), based on a survey with Herschel.

We selected a sample of 89 sources, with 40 of them known to be confirmed members (Gaia EDR3) associated with CMa. The mean error-weighted parallax was converted to the distance of 1099 ± 25 pc, which is in excellent agreement with previous results for the CMa region (Claria 1974; Tovmasyan et al. 1993; Shevchenko et al. 1999). Using the WISE colors, the sources were characterized according with the IR-excess. We are mainly interested here in Classes I and II that may have circumstellar disks. All of these disk-bearing stars are found around the filamentary structure of the cloud, despite several of them not being embedded, but more likely located in the cloud foreground. The color-magnitude diagram constructed with the $G_{Gaia}$ photometry was used to verify whether the selected sources truly are pre-main sequence stars. The ages are less than 5 Myr for most of the sources, coinciding with ages estimated for the cluster found in the opposite side of the CMa shell. Moreover, as shown in Fig. 5 (right panel) and discussed below, the presence of embedded objects corresponding to protostellar phase (Class 0 and Class I sources) is confirmed in our sample. Since Class 0 and Class I stars have typical ages of $10^{-2}$–$10^{-1}$ yr, they can be considered a direct evidence for sequential star formation in the region.

The kinematic analysis reveals the presence of two structures representing different parts of the cloud. A main structure, exhibiting $V = 15 ± 1.2$ km s$^{-1}$, is formed from N to S in an extended stripe where most of the dense cores are found and YSOs are associated with. The secondary structure, seen at $V = 17.4 ± 1.2$ km s$^{-1}$, grows from the south-west to the center of Fig. 3 (middle panel). The evidence of outflows is remarkable from the broad wings in the CO rotational line profiles observed in six dense cores, which are believed to be sites of protostellar activity, as indicated by their association with IR sources; this shows that a burst of star formation is currently ongoing. Follow-up observations, such as near-IR spectroscopy aimed at obtaining radial velocity of the members, are required to confirm the trends of stellar members following the cloud structure observed for this limited sample of objects associated with the studied region.

Despite the fact that these are partial results, our findings shed some light on the understanding of star formation in CMa. The age of the Class II population is consistent with the age and timescale of SNRs (Fernandes et al. 2019). The similarity of the young stellar population properties on eastern and western sides of the shell supports the scenario of a large-scale gravitational collapse of the shell, most likely induced by SN explosions.

We tentatively suggest that the presence of young protostellar population (with massive or intermediate-mass objects, as indicated by the strong outflow emission) or a second episode of star formation has recently taken place. The distribution of YSOs in the two gas layers at 15 and 17 km s$^{-1}$ suggests that local events on the eastern side (the region surveyed at IRAM) have contributed to driving the current star formation process. Our observations of the region altogether support the large-scale scenario of SNR that are shock-driven, but other processes on smaller scales appear to have influenced – and possibly induced – local star formation.

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Appendix A: Additional tables

Table A.1. Membership probability, parallax, proper motion, and Gaia EDR3 photometry.

| Gaia EDR3 | P | σ | μ_α | μ_δ | G | G_{BP} | G_{RP} |
|-----------|---|---|-----|-----|---|--------|--------|
| 3045239083971370112 | 87 | 0.77 ± 0.17 | −3.21 ± 0.16 | 0.91 ± 0.15 | 18.65 | 20.43 | 17.24 |
| 3045208886056506112 | 13 | 1.69 ± 1.10 | −2.52 ± 0.86 | 0.97 ± 0.16 | 20.33 | 21.63 | 18.78 |
| 3045225516172964864 | 95 | 0.66 ± 0.02 | −3.32 ± 0.02 | 0.74 ± 0.02 | 13.80 | 14.77 | 12.74 |
| 304522929445342592b | 92 | 1.31 ± 0.19 | −3.26 ± 0.18 | 0.98 ± 0.16 | 18.80 | 20.42 | 17.43 |
| 3045227749555916032c | 91 | 0.61 ± 0.14 | −3.11 ± 0.16 | 0.88 ± 0.13 | 17.93 | 19.59 | 16.63 |
| 304531010773079168 | 90 | 0.79 ± 0.10 | −3.02 ± 0.08 | 1.04 ± 0.09 | 17.94 | 19.06 | 16.22 |
| 304520895047942208 | 83 | 1.12 ± 0.26 | −3.28 ± 0.20 | 1.11 ± 0.18 | 18.89 | 20.72 | 17.57 |
| 30452374703416320 | 82 | 1.63 ± 0.39 | −3.52 ± 0.34 | 1.09 ± 0.33 | 19.89 | 21.26 | 18.52 |
| 3045235785435946624 | 79 | 0.72 ± 0.32 | −3.13 ± 0.26 | 1.22 ± 0.24 | 19.03 | 20.96 | 17.65 |
| 30451714125787200 | 78 | 1.00 ± 0.30 | −3.49 ± 0.28 | 0.90 ± 0.29 | 19.01 | 20.52 | 17.75 |
| 30452598525352384d | 65 | 0.97 ± 0.11 | −2.93 ± 0.11 | 0.43 ± 0.10 | 17.29 | 19.13 | 15.91 |
| 304511614758900736 | 65 | 0.57 ± 0.52 | −4.38 ± 0.53 | 1.48 ± 0.54 | 19.99 | 22.18 | 15.87 |
| 304514804796665984d | 63 | 1.02 ± 0.51 | −3.17 ± 0.44 | 2.00 ± 0.48 | 19.85 | 21.54 | 18.39 |
| 304521407008077600 | 27 | 0.92 ± 1.18 | −2.78 ± 0.90 | 0.44 ± 1.00 | 20.66 | 21.37 | 19.22 |
| 3045234170527254656 | 21 | 0.45 ± 0.10 | −3.00 ± 0.10 | 0.87 ± 0.09 | 17.39 | 19.19 | 16.07 |
| 30452357845360040 | 21 | 1.47 ± 0.80 | −3.48 ± 0.62 | 0.54 ± 0.63 | 20.26 | 21.51 | 18.81 |

Notes: The objects are distinguished by: Class I (top); Class II (middle); Class III (bottom), according with Table A.2. Stars identified as Hα emitters are indicated by (a) ID 381; (b) ID 387; (c) ID 390; and (d) ID 392, where the ID numbers are given by Pettersson & Reipurth (2014).
Table A.2. Infrared photometry for stellar populations.

| Gaia EDR3 | 2MASS       | J          | H          | K          | W1         | W2         | W3         | W4         | Class |
|-----------|-------------|------------|------------|------------|------------|------------|------------|------------|-------|
| 3045239083971370112 | 0711437-1152298 | 14.44      | 12.88      | 11.82      | 10.97      | 9.82       | 6.99       | 4.61       | I     |
| 304520886056506112 | 0711976-1214324 | 15.55      | 14.05      | 13.13      | 11.60      | 10.46      | 7.88       | 5.63       | I     |
| 30452255172964864 | 0711380-1206336 | 10.79      | 9.62       | 8.65       | 7.62       | 7.00       | 4.55       | 2.66       | II    |
| 304522929445342592 | 0711424-1157517 | 15.24      | 13.89      | 12.94      | 11.40      | 10.61      | 8.49       | 6.41       | II    |
| 304522749555916032 | 0711439-1203191 | 13.39      | 12.11      | 11.29      | 10.32      | 9.66       | 7.51       | 5.74       | II    |
| 3045313001773079168 | 0711362-1210420 | 14.09      | 12.89      | 12.24      | 10.14      | 9.11       | 6.87       | 5.64       | II    |
| 304520850479472408 | 0711423-1214061 | 15.06      | 13.94      | 13.45      | 12.66      | 11.91      | 8.71       | 5.69       | II    |
| 304523734703416320 | 0711435-1152374 | 15.79      | 14.37      | 13.56      | 12.79      | 12.13      | 10.54      | 5.78       | II    |
| 30452385845946624 | 0711425-1154273 | 15.02      | 13.74      | 12.92      | 11.77      | 11.20      | 9.96       | 8.38       | II    |
| 304511714215872000 | 0711308-1216043 | 15.21      | 14.02      | 13.45      | 12.73      | 11.98      | 9.56       | 7.42       | II    |
| 304521599852539284 | 0711420-1230377 | 13.20      | 11.99      | 11.32      | 10.40      | 9.57       | 7.20       | 4.77       | II    |
| 304511614757870036 | 0711358-1217599 | 15.54      | 14.04      | 13.27      | 12.56      | 12.03      | 9.86       | 7.85       | II    |
| 304511480479665984 | 0711407-1217153 | 15.73      | 14.87      | 14.32      | 13.98      | 13.48      | 10.03      | 7.68       | II    |
| 3045220708077600 | 0711284-1209146 | 15.65      | 14.24      | 13.20      | 12.39      | 11.49      | 9.07       | 6.47       | II    |
| 304522520227254656 | 0711475-1158460 | 13.72      | 12.58      | 12.07      | 11.39      | 10.69      | 8.47       | 6.48       | II    |

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