3D dynamics of the Orion cloud complex

Discovery of coherent radial gas motions at the 100-pc scale

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ABSTRACT

We present the first study of the 3D dynamics of the gas in the entire Southern Orion cloud complex. We used the YSO’s proper motions from Gaia as a proxy for the gas proper motion, together with gas radial velocities from archival CO data, to compute the space motion of the different star-forming clouds in the complex, including sub-regions in Orion A, Orion B, and two outlying cometary clouds. From the analysis of the cloud’s orbits in space and time we find that they were closest about 6 Myr ago and are moving radially away from roughly the same region in space. This coherent 100-pc scale radial motion supports a scenario where the entire complex is reacting to a major feedback event that we name the Orion−6 event. This event, that we tentatively associate with the recently discovered Orion X population, shaped the distribution and kinematics of the gas we observe today, although it is unlikely to have been the sole major feedback event in the region. We argue that the dynamics of most of the YSOs carry the memory of the feedback-driven star formation history in Orion and that the majority of the young stars in this complex are a product of large-scale triggering, that can raise the star formation rate by at least an order of magnitude, as in the case of the Orion A’s Head (the Integral Shape Filament). Our results imply that at the genesis of the Orion Nebula Cluster (and NGC 2023/2024 in Orion B) lies a feedback/compression/triggering process.

Key words. stars: formation - molecular cloud: Orion A - molecular cloud: Orion B - photometry: infrared - astrometry: parallaxes - astrometry: proper motions - radial velocities

1. Introduction

Nearby molecular clouds are the only places where observations with the necessary detail can be made to test theories of star formation and to infer the physics behind this process. The Orion star-formation complex (Bally 2008) is one of these regions, since it is the closest region with ongoing massive star formation, and with a wide variety of different star formation environments. Much is known for this well-studied region such as mass estimates (atomic and molecular gas content), the stellar populations (young stellar objects, YSOs, OB associations, and clusterings), several fundamental statistics like the initial mass function or star formation rates, and line-of-sight dynamics (e.g., CO, Kutner et al. 1977; Maddalena et al. 1986; Bally et al. 1987; Dame et al. 2001; Nishimura et al. 2015). The origin for the gradient has been attributed in the past to either rotation (Kutner et al. 1977; Maddalena et al. 1986; Bally et al. 1987; Dame et al. 2001; Nishimura et al. 2015). The origin for the gradient has been attributed in the past to either rotation (Kutner et al. 1977; Maddalena et al. 1986) or large-scale expansion

Recently, we used Gaia DR2 parallaxes to determine distances to the giant molecular cloud (GMC) Orion A (Großschedl et al. 2018, hereafter, Paper I), by using YSO parallaxes as proxy for cloud distances. This analysis revealed a striking distance gradient from “Head” to “Tail”1, resulting in an almost 100 pc long structure, meaning that the cloud is at least twice as long as previously assumed. This distance gradient was already suggested by other methods, for example, by Schlafly et al. (2014) or Kounkel et al. (2017a), and then confirmed with Gaia data by Kounkel et al. (2018), Paper I, Zucker et al. (2020), or Rezaei Kh. et al. (2020). The cloud’s 3D structure analysis in Paper I also revealed that the Head of the cloud seems to be “bent” with respect to its tail, suggesting that external forces have shaped the region in the past. Knowing a cloud’s 3D spatial structure allows one to break fundamental degeneracies, such as the interpretation of molecular line data (position-position-velocity, PPV, e.g., Zucker et al. 2018b). For example, it was long known from molecular line observations of the Orion A cloud, that there is a “jump” in radial velocities (∆RV ~ 2 km/s) at the location of the ONC and a mystifying velocity gradient from Head to Tail (e.g., CO, Kutner et al. 1977; Maddalena et al. 1986; Bally et al. 1987; Dame et al. 2001; Nishimura et al. 2015). The origin for the gradient has been attributed in the past to either rotation (Kutner et al. 1977; Maddalena et al. 1986) or large-scale expansion

1 We refer to the high-mass star-forming parts of the cloud as Head, including the Integral Shaped Filament (ISF. Bally et al. 1987) and the Orion Nebula Cluster (ONC, O’Dell et al. 2008), and the low-mass star-forming parts as Tail (L1641, L1647, Allen & Davis 2008a).
due to stellar winds (Bally et al. 1987). The third spatial dimension promises to test current Orion A models by disentangling radial velocity from 3D space (PPPV).

In this paper we investigate if an external feedback event could be responsible for the inferred 3D space of the cloud and its bulk motion, as well as the overall shape of the Orion complex. Such feedback mechanisms, from previous generations of nearby massive stars, were already proposed in the past, for example, to explain the Orion-Eridanus superbubble (e.g., Bally et al. 1987; Ogura & Sugitani 1998; Lee & Chen 2009; Ochsendorf et al. 2015; Pon et al. 2016). Alternatively, Fukui et al. (2018) proposed that a cloud-cloud collision shaped the Orion A GMC near the ONC, which could also explain the observed bent Head (see also Nakamura et al. 2012). The Head of the cloud produced about a factor ten more stars compared to the Tail within the last 3 to 5 Myrs as inferred from the distribution of YSOs with infrared-excess along the cloud (Großschedl et al. 2019b). Such increased star formation activity would fit a picture of triggered star formation by an external event at one end of the cloud while explaining the cloud’s 3D shape.

A crucial piece of information, needed to disentangle the various structure formation scenarios in Orion, is its 3D spatial motion, requiring measurements of the unknown cloud’s proper motions (PM). An analysis of the 3D motions of individual sub-regions in Orion A would ideally reveal the physical status of the cloud (collapse, contraction, rotation, collision) and be a useful discriminant between the various scenarios, or even provide new insights into a new interpretation of the observables.

To directly measure proper motions of clouds is virtually impossible. However, and on average, one can equate cloud proper motion with the proper motion of the youngest embedded sources inside a cloud. Using YSOs as a proxy for cloud proper motions is, to first order, justified because (1) these objects are still very young and close to their birth sites (e.g., Dunham et al. 2015; Heiderman & Evans 2015; Großschedl et al. 2019a) and (2) there is solid evidence that the YSOs share, on average, the same velocity properties as their parental cloud. For example, the YSOs in Orion A share the same radial velocity as the molecular gas (e.g., Fűrész et al. 2008; Tobin et al. 2009; Hacar et al. 2016b, and Fig. 2), also seen in Orion B (e.g., Kounkel et al. 2017b, and Fig. 3). It is then very likely that, on average, YSOs have the same proper motion as the gas from which they formed. Until recently, there were no proper motions available for a statistically significant sample of young sources in the Orion molecular clouds. There have been estimates of proper motions of a handful of young embedded sources from VLBI observations (e.g., Menten et al. 2007; Kounkel et al. 2017a; Reid et al. 2014, 2016, 2019), but they often do not agree with each other. A possible reason for this situation is the sample size and hence the possibility that peculiar motions could dominate a small sample. Additionally, VLBI observations often incidentally targeted multiple systems, which does not allow to evaluate the average motion of their region of origin. Proper motions of less embedded YSOs observed by Gaia are not only the best available today, but they have more than an order of magnitude better statistics.

The goal of this paper is to derive, for the first time, the 3D space motions of sub-regions in the Orion cloud complex to understand the region’s large-scale dynamics and possibly illuminate the star formation history and existing formation mechanism scenarios for this benchmark region. In the following sections, we will describe the necessary steps to combine Gaia DR2 parallaxes and proper motions of YSOs with radial velocity measurements from spectroscopic surveys and molecular line observations (Data Sect. 2) to achieve an estimate of the space motion of the gas. The methods are presented in Sect. 3, the results in Sect. 4, in Sect. 5 we discuss our results, and we summarise our work in Sect. 6.

2. Data

In this section, we describe the studied sub-regions and the data needed to enable an analysis of the 3D spatial motion of molecular clouds in Orion. The most prominent clouds in Orion are the GMC’s Orion A and Orion B, which are both active star-forming regions, both containing hundreds of YSOs. Additionally, we investigated two cometary-shaped outlying clouds, L1616 and IC2118 (Alcalá et al. 2008), located to the South-West of Orion A. These two clouds show sufficient star formation to be included in our work. Henceforth, we address the three studied main regions separately as Orion A, Orion B, and outlying clouds. To derive the average positions and velocities for each region, we used Gaia DR2 parallaxes and proper motions of YSO members of the studied clouds (Sect. 2.1), and gas radial velocities obtained from CO emission line surveys (Sect. 2.2). An overview of the region is shown in Fig. 1 and a more detailed description of each sub-region is given in Sect. 2.3. We refer to

\footnote{Gaia Archive: \url{https://gea.esac.esa.int/archive/}}
Fig. 2. Top: Position-Velocity Diagram ($l$ vs $v_{LSR}$) for gas and YSOs in Orion A. The gas velocities are taken from the $^{12}$CO(2-1) emission line map from Nishimura et al. (2015), integrated over the velocity range $0 \text{ km/s} < v_{LSR} < 17 \text{ km/s}$. Only pixels within a smoothed column-density contour of $A_K > 0.5$ mag were used to avoid contamination by background emission. The magenta dots show the selected YSO sample that satisfies the APOGEE-2 quality criteria. The YSO's $v_{LSR}$ was converted with the standard solar motion from Kerr & Lynden-Bell (1986), which we assume to match best to the gas $v_{LSR}$. There are shifts between gas and YSO $v_{LSR}$, however, this could be due to errors, or inconsistent LSR conversion, hence an unambiguous interpretation of any shift is not possible. Bottom: Map of the pixels that were used for the PV-diagram within the extinction contour. The color-scale shows $v_{LSR}$, and highlights again the RV gradient. The upper Tail to the East was excluded due to uncertain distance estimates, lower intensity CO measurements, and little star formation activity. The average positions of the studied eight sub-regions along the cloud are marked with gray circles. The bins enclosing NGC 1977 and NGC 1988 are excluded (gray shaded area, top panel), since the gas and YSOs get decoupled.

Appendix A for a detailed description of the quality cuts and YSO sample selections. For clarity, we introduce here the observed position and velocity parameters that are used throughout the paper:

- $\alpha, \delta$ (deg): Right Ascension and Declination
- $l, b$ (deg): Galactic longitude and latitude
- $\varpi$ (mas): parallax
- $d$ (pc): distance as derived from $1/\varpi$
- $\mu_\alpha, \mu_\delta$ (mas/yr): proper motion along $\alpha$, $\mu_\delta$ (mas/yr): proper motion along $\delta$
- $v_{HEL}$ (km/s): Heliocentric radial velocity
- $v_{LSR}$ (km/s): radial velocity relative to the local standard of rest (LSR)

2.1. Collecting YSO samples

We used YSOs with infrared-excess (Class II or younger classes) for our analysis, to include only the youngest sources for each cloud, which are the most likely candidates to be located still close to their birth-sites. To get the best available YSO statistics we combined archival YSO catalogs with additional YSO selections (Appendix A), while all YSO samples include a Gaia quality criteria cut (Appendix A.1). First, we collected data from the literature containing YSOs and/or radial velocity measurements of young stellar members in the Orion regions of interest (Alcalá et al. 2004; Flaherty & Muzerolle 2008; Guieu et al. 2010; Megeath et al. 2012, 2016; Kounkel et al. 2017b, 2018; Großschedl et al. 2019a; Guieu et al. 2010).
2.2. Gas radial velocities

To get a direct estimate of a cloud’s line-of-sight motion, we used gas radial velocities (RVs) from molecular emission line surveys. Primarily, we used the Nishimura et al. (2015, hereafter N15) molecular emission line survey of $^{12}$CO(2-1) (at 230.54 GHz) that covers both Orion A and large parts of Orion B. We compared N15 to the Kong et al. (2018) CARMA-NRO Orion Survey, a high-resolution survey of the Northern parts in Orion A and found that N15 $^{12}$CO(2-1) RVs agree on average well with $^{12}$CO(1-0), $^{13}$CO(1-0), and C$^{18}$O(1-0) CARMA RVs. Since we are only interested in average motions, the resolution of N15 is sufficient for our purposes. When other molecular line observations were used, we list them in the Sects. 2.3.1 to 2.3.3, where we give short overviews for each of the three main regions and briefly address issues concerning data availability.

Using different molecular emission line surveys could imply systematic differences between these studies, that are not easy to account for. Moreover, each of these studies reports the gas radial velocities relative to the local standard of rest ($v_{LSR}$). For our purposes, however, we require the heliocentric radial velocity ($v_{HEL}$) as starting condition to convert the motions of all regions consistently to motions relative to LSR. Unfortunately, the conversions from $v_{HEL}$ to $v_{LSR}$, as derived from gas observations, are not mentioned explicitly in the various publications (see also the discussion in Appendix B), hence they can not be compared with each other at face value. We converted back to $v_{HEL}$ with the best possible guess for each data set. For N15 we assumed the widely used standard solar motion of 20 km/s as stated in Kerr & Lynden-Bell (1986, hereafter KL86, see also Table B.1). We used this LSR conversion to determine $v_{HEL}$ for the gas, if not stated otherwise. Inaccurately converted velocities can lead to additional errors in the evaluation of the dynamical evolution of the studied regions. This does, however, not affect the main result in this work, as addressed in Appendix B.

2.3. Studied clouds

Here we provide an overview for the studied molecular clouds in Orion, while we will put a focus on data availability for individual regions. Especially, we will put a focus on the evaluation of radial velocities ($v_{HEL}$), since this observable is the most homogeneously derived value in our study. Detailed numbers are given in Table 2 and in Appendix A.

2.3.1. Orion A

The GMC Orion A is the best-studied cloud in our sample. Hence a wealth of data is available for this region, including information on the stellar and the gaseous content. Orion A includes the following cloud parts, which are also separated in this paper and are included in the analysed sub-regions; these are the Orion Molecular Clouds OMC-2/3, OMC-1, OMC-4/5 (Peterson & Megeath 2008; Muench et al. 2008, O'Dell et al. 2008, Head of Orion A), and the Lynds dark clouds4 L1641, and L1647 (Allen & Davis 2008b, Tail of Orion A). L1641 will be further separated into the North, Center, Center-South, and South sub-regions (L1641-N, L1641-C, L1641-C/S, L1641-S, see Fig. 2).

3 https://www.sdss.org/dr16/irspec/spectro_data/

4 Lynds dark clouds are always abbreviated with “L” in-front of the individual number.
A YSO sample, containing 2980 YSOs with IR-excess, a catalog based on a Spitzer\cite{2004Spitzer} and WISE/2MASS/VISION\cite{2006WISP} selection (see also Megeath et al. 2012, 2016; Furlan et al. 2016; Meingast et al. 2016). After applying Gaia quality criteria (Appendix A.1) we were left with about 33\% of the original YSO catalog. Radial velocities from APOGEE-2 are also available for a significant sub-sample of YSOs (~31\%) with applied RV quality criteria (Appendix A.2). When combining Gaia and APOGEE-2 there are about ~15\% of the original YSO catalog left (see also Table 2). To obtain gas RVs for Orion A we used the mentioned N15\textsuperscript{12}CO(2-1) map which covers the whole cloud area.

### 2.3.2. Orion B

The same surveys that cover Orion A largely cover the main parts of Orion B. A Spitzer/2MASS selected YSO sample for Orion B (Megeath et al. 2012, 2016) contains 663 YSOs candidates with IR-excess, of which about 25\% survive our Gaia quality criteria. Spitzer covered the most prominent cloud parts, which can be split up into three regions; the two clusters in L1630, NGC2023/2024 and NGC2068/2071, and L1622 (e.g., Lada et al. 1991; Reipurth 2008; Meyer et al. 2008; Bally et al. 2009; Megeath et al. 2012). There is no similar extended YSO selection done for Orion B as in Großschedl et al. (2019a) for Orion A. Due to the smaller sample compared to Orion A, we searched for additional YSO candidates in the surroundings (beyond Spitzer observed regions) using the WISE/2MASS selection, with the criteria and numbers given in Appendix A.3. Following, we discuss the Orion B main cloud (L1630) and L1622 separately due to different data coverage.

**L1630 South and North:** The Orion B main cloud L1630 can be split into two major components with significant active star formation, which are the clusters NGC2023/2024 in the South (L1630-S), and NGC2068/2071 in the North (L1630-N) (e.g., Lada et al. 1991; Meyer et al. 2008). For these parts of Orion B we used N15\textsuperscript{12}CO(2-1) gas RVs. These two parts contain the majority of the Spitzer selected YSO candidates (635, 96\%) from the Megeath et al. (2012) survey, and we were able to extend the YSO sample with the mentioned WISE/2MASS selection (Appendix A.3). There are APOGEE-2 RVs available for these regions. We compared APOGEE-2 RVs to other RV measurements in Orion B of young stellar members by Flaherty & Muzerolle (2008) and Kounkel et al. (2017b), and find that they are generally in agreement with each other within the errors. If anything, there is a slight blue-shift of the Kounkel et al. (2017b) RVs in NGC2023 relative to APOGEE-2 RVs, while not significant within the errors. For our analysis, we used APOGEE-2 radial velocities due to smaller measurement errors and consistency with Orion A. After applying the Gaia quality criteria and further individual region selections (Appendix A.4, Fig. A.3), we ended up with 58 and 70 YSOs for L1630-S and L1630-N, respectively, while 36 and 45 of these survive the additional APOGEE-2 quality criteria (Appendix A.2).

**The L1622 cloud:** This is a small cometary cloud North-East to the Orion B main clouds and is likely located in-front of these (Reipurth 2008). It is also called Orion East in Wilson et al. (2005). The Megeath et al. (2012) Spitzer catalog for L1622 contains 28 YSO candidates. After extending the sample with the WISE/2MASS YSO selection (Appendix A.3), applying Gaia quality criteria and additional individual selection criteria (Appendix A.4, Fig. A.3) we ended up with 8 YSOs for L1622. This cloud was not covered by APOGEE-2, but RV measurements are available from Kounkel et al. (2017b) for four young sources, which match the RV and distance criteria of that region. On average these YSOs have $v_{HEL} = (19.3 \pm 1.2)$ km/s. Gas $v_{LSR}$ for L1622 are reported in several independent studies. Maddalena et al. (1986) listed this cloud as CO clump Nr. 38 and report a value of $v_{LSR}$ at 0.7 km/s. The region was also covered by the large-scale survey of Dame et al. (2001), and discussed in Wilson et al. (2005)\footnote{Spitzer Space Telescope, Werner et al. (2004)\footnote{Viena Survey In Orion, and ESO VISTA NIR survey by Meingast et al. (2016)}} who find on average a $v_{LSR}$ of about 1 km/s toward L1622. Moreover, Park et al. (2004) present a study of star-less cores including parts of L1622, which have on average a $v_{LSR}$ of about 1.13 km/s. Finally, Kun et al. (2008) observed the cloud with NANTEN, providing $12^{CO}$ and $13^{CO}$ emission line maps. They report an average $v_{LSR}$ of 1.17 km/s toward L1622, in rough agreement with the previous studies. We adopt the value from Kun et al. (2008), which is converted to heliocentric $v_{HEL} = 17.96$ km/s.

### 2.3.3. Outlying clouds

We include in our study two cometary-shaped star-forming clumps to the South-West of Orion A, which are part of the so called outlying clouds (Alcalá et al. 2008). This group includes L1616 and IC 2118 (Witch Head Nebula). Close to these regions lies L1634, which we first intended to included in our analysis. However, the region shows an apparent overlap between two seemingly distinct clouds in reflection (optical) and dust emission, and a clear determination of YSO membership in this region was not possible. As a consequence, we did not include L1634 in our analysis.

**The L1616 cloud:** This is a small clump in the outlying clouds (Park et al. 2004; Alcalá et al. 2004; Gandolfi et al. 2008; Alcalá et al. 2008). Alcalá et al. (2004) present a list of 30 PMS stars near L1616, of which 22 have measured radial velocities. After adding YSOs with the WISE/2MASS selection (Appendix A.3) and applying Gaia quality criteria and individual selections, we ended up with 14 YSO candidates (Appendix A.4, Fig. A.4). The RV-measurements in Alcalá et al. (2004) scatter around $v_{HEL} = 22.3 \pm 4.6$ km/s (see also Gandolfi et al. 2008). This average radial velocity is consistent with gas RVs reported in Maddalena et al. (1986), CO clump Nr.13 who report a value of $v_{LSR} \sim 7.7$ km/s, which is converted to $v_{HEL} \sim 22.6$ km/s, when using the standard solar motion from Mihalas & Binney (1981). However, we ended up with only four YSOs from Alcalá et al. (2004) that are within our selection criteria, which have on average a $v_{HEL}$ of 24.5 \pm 2.7 km/s. The individual measurement errors of these four sources are on the same order as the standard deviation (2 to 3 km/s), hence the discrepancy to gas $v_{HEL}$ is likely not significant.

**IC2118 – Witch Head Nebula:** This is a reflection nebula South-East of L1616, in the proximity of the B-star Rigel ($\sigma = 3.78$ mas, van Leeuwen 2007, hence, roughly 30 pc separated from L1616). Guieu et al. (2010)\footnote{Data from Harvard Dataverse (Wilson et al. 2011), https://dataverse.harvard.edu/dataset.xhtml?persistentId=doi:10.7910/DVN/KW6HM7} reports 17 pre-main-sequence stars for IC2118, of which 10 are Spitzer selected YSOs. The majority is located at the Northern part of IC2118, at the top of the Witch Head Nebula. We also applied our WISE/2MASS selection criteria in this region (see Appendix A.3). This, however, did not change the original Guieu et al. (2010) selection.
within the \textit{Gaia} quality criteria. Our final sample for IC2118 contains five YSOs (Appendix A.4, Fig. A.4). We extracted gas RV measurements for this region from \textit{Kun et al. (2001)} \textit{({\textsuperscript{12}}CO(1-0) NANTEN 4m Radio Telescope)}. They report a $v_{\text{LSR}}$ of $-2.2 \pm 1.8$ km/s for the northern part of the cloud, which corresponds to the region where the small cluster of YSOs is located. This converts to $v_{\text{HEL}}$ of $15.4$ km/s when using the standard solar motion from KL86. \textit{Kun et al. (2001)} report radial velocity variations across the whole Witch Head Nebula of about $10$ km/s, while in this paper we only focus on the small part at the top of the cloud containing YSOs, and we will not discuss this gradient further. For this cloud there are no stellar radial velocities available to be compared to gas radial velocities.

3. Methods

In this section we describe our methods to evaluate the 3D space motions of molecular clouds in Orion. First, we demonstrate the validity of using YSOs as proxy for cloud proper motions and parallaxes. Next, we present the methods used to obtain the average positions and motions for the individually discussed clouds. Finally, we introduce our approach to estimate the orbits of the clouds in the Milky Way and their 3D space motions.

3.1. YSOs as proxies for cloud parameters

We used YSOs with infrared excess to indirectly determine the proper motions and distances of the studied star-forming molecular clouds. These young stars ($\leq 3$ Myr, e.g., \textit{Dunham et al. 2015}) are still close to their birth sites (e.g., \textit{Heiderman et al. 2010; Gutermuth et al. 2011; Großschedl et al. 2019a}), and it is well established in the literature that young stars in general share the radial velocities of their parental molecular clouds (e.g., \textit{Furész et al. 2008; Tobin et al. 2009; Hacar et al. 2016b}). The observed agreement suggests that, on average, also the proper motions and distances of gas and YSOs should be approximately the same.

For our purposes, we used Class II (or earlier class) YSOs in order to retain only the youngest possible selection to maximize the chances that the young stars share the same space motion as the gas. We did not include Class III sources (e.g., \textit{Pilliitteri et al. 2013}), but a first analysis indicates that many Class III candidates still share the same overall motions and distances as the Class II candidates. This suggests that, in the future, also Class III samples could provide important insight on the dynamics of molecular cloud complexes, when no or too little Class II members are available.

3.2. Evaluating positions and motions for the individual clouds’ sub-regions

To obtain the 6D parameters, we determined the average 3D position of each sub-region from their projected 2D positions ($l, b$, or $\alpha, \delta$) and average \textit{Gaia} DR2 parallaxes ($\sigma$). 3D motions were obtained from \textit{Gaia} DR2 proper motions ($\mu_l, \mu_b$, or $\mu_{\alpha}, \mu_{\delta}$), combined with gas radial velocities ($v_{\text{HEL}}$). To get the averages we calculated the mean of $\sigma, \mu_l, \mu_b$, and $v_{\text{HEL}}$, and we parameterized the scatter with the standard deviation of the mean ($\sigma$). The distances $d$ (pc) were derived by inverting the parallaxes. This approach does not include any systematic correction (\textit{Lindgren et al. 2018; Stassun & Torres 2018}), since it is uncertain how and if any systematics apply for the region enclosing Orion. Moreover, we did not use an inference procedure to account for the non-linearity of the transformation or the asymmetry of the resulting probability distribution (see \textit{Bailer-Jones et al. 2018}), since the resulting distances do not divert significantly for the distance of Orion (within about $300$ pc $< d < 500$ pc).

Due to differences of the three chosen regions (Orion A, Orion B, outlying clouds) we will shortly discuss them individually in the following subsections. For each region, we performed individual checks on the validity of using YSOs as a proxy for cloud parameters by comparing YSO and gas radial velocities.

3.2.1. 6D parameter determination for Orion A

Since Orion A covers a quite large area in the sky (almost $20$ deg$^2$), shows gradients in both distance and velocity, and most importantly, since the 3D shape shows a bent structure, we decided to split the region into eight sub-regions (see also Sect. 2.3.1). First, to get the cloud’s line of sight motions, we only extracted those radial velocity measurements from the $^{12}$CO map that fall within a specific extinction contour (smoothed outer contour at $A_K = 0.5$ mag) to eliminate possible background contamination. This approach reduced the velocity scatter in the PV-diagram significantly (Fig. 2, compare to Figure 1 in \textit{Hacar et al. 2016b}). Additionally, we excluded the North-East part of Orion A’s Tail (see Fig. 2, the outlined contour), due to uncertain distance estimates for this region and low YSO statistics.

Next, we split the cloud based on known sub-regions near the Head (see also \textit{Getman et al. 2019}), and based on radial velocities at the Tail, since there are regions with almost constant velocities, interrupted by velocity-jumps of about $1$ to $2$ km/s. The cloud-separations were applied at the following positions along $l$ (deg): $214.85, 213.73, 212.32, 211.23, 210.57, 209.70, 209.23$, $208.85, 208.57, 208.57, 208.20$. These sub-regions correspond to known cloud parts as introduced in Sect. 2.3.1. The PV-diagram in Fig. 2 illustrates this approach.

The average properties were then determined from the mean of the parameters within these bins. To determine $v_{\text{HEL}}$ we used the average $v_{\text{LSR}}$ measurements of the gas from N15, and converted it to $v_{\text{HEL}}$ using the KL86 standard solar motion. We then compared to YSO radial velocities ($v_{\text{HEL}}$ of YSOs was converted with KL86 to $v_{\text{LSR}}$ for Fig. 2), which follow on average the same trend as the gas (within the standard deviation). This validates our assumption to use YSOs as proxy for cloud parameters, and we averaged the YSO’s proper motions and parallaxes within the same bins. We excluded the most Western part that overlaps with NGC 1977, since this cluster seems to be decoupled from the gas in projection, and the velocities show a deviation of YSOs versus gas. Average $l$ values for each sub-region were determined from the mid bin positions, and average $b$ values were chosen manually to match with regions of high column-density (these positions match well with average YSO $b$ positions).

3.2.2. 6D parameter determination for Orion B

Orion B is split into three main components, as also described in Sect. 2.3.2. For the two sub-regions in L1630, we used the N15 map to determine the average $v_{\text{HEL}}$ from the gas, similar as for Orion A. The corresponding PV-Diagram is shown in Fig. 3, which shows YSO’s and gas $v_{\text{LSR}}$ for the sub-regions L1630-S/N. Within the errors, these two are in agreement with each other, while in L1630-N the YSO RVs seem to be slightly red-shifted (on average about $1.5$ km/s). It is not clear if this is a significant shift. For example, \textit{Kounkel et al. (2017b)} do not find
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Table 1. Overview of the discussed 13 subregions, including the cluster Orion X.

| Label | Cloud | Sub-region | $l$ | $b$ | $a$ | $d$ | $\sigma_a$ | $\sigma_d$ |
|-------|-------|------------|-----|-----|-----|-----|-----------|-----------|
| 1     | Orion A | L1647      | 214.29 | -19.83 | 85.62 | -10.05 | 0.20 | 0.18 |
| 2     | Orion A | L1641-S    | 213.03 | -19.25 | 85.63 | -8.73 | 0.28 | 0.49 |
| 3     | Orion A | L1641-S/C  | 211.78 | -19.23 | 85.13 | -7.66 | 0.38 | 0.31 |
| 4     | Orion A | L1641-C    | 210.90 | -19.52 | 84.50 | -7.04 | 0.43 | 0.23 |
| 5     | Orion A | L1641-N    | 210.13 | -19.62 | 84.09 | -6.44 | 0.34 | 0.24 |
| 6     | Orion A | OMC-4/5    | 209.47 | -19.63 | 83.79 | -5.89 | 0.25 | 0.19 |
| 7     | Orion A | OMC-1      | 209.04 | -19.44 | 83.78 | -5.44 | 0.25 | 0.17 |
| 8     | Orion A | OMC-2/3    | 208.71 | -19.22 | 83.84 | -5.06 | 0.29 | 0.16 |
| 9     | Orion B | L1630-N    | 206.59 | -16.35 | 85.46 | -1.95 | 0.17 | 0.29 |
| 10    | Orion B | L1630-N    | 205.25 | -14.22 | 86.73 | 0.19  | 0.14 | 0.19 |
| 11    | Orion B | L1622      | 204.77 | -11.90 | 88.56 | 1.70  | 0.07 | 0.07 |
| 12    | Outlying Cloud | L1616 | 203.50 | -24.70 | 76.72 | -3.33 | 0.18 | 0.10 |
| 13    | Outlying Cloud | IC2118 | 206.38 | -25.94 | 76.84 | -6.21 | 0.10 | 0.10 |
| 14    | -      | Orion X    | 206.20 | -22.08 | 80.20 | -4.29 | 1.37 | 1.41 |

Notes. (a) Orion X is included in this table for completeness. It is used to set the center position of the coordinate system in Figs. 7 to 9.

Table 2. Overview of 6D average properties for the subregions, including Orion X.

| Sub-region | $N_{ts}$ | $\alpha$ | $d$ | $\sigma_a$ | $\sigma_d$ | $v_{lsr}$ | $v_{lsr}$ | $v_{lsr}$ |
|------------|----------|--------|-----|-----------|-----------|-----------|-----------|-----------|

Notes. (a) Reference for stellar radial velocities given in $v_{\text{HEL}}$, as derived from stellar spectra. (b) Reference for gas radial velocities given in $v_{\text{LSR}}$, derived from $^{12}$CO emission line surveys. (c) The average $v_{\text{HEL}}$ of the YSOs is converted to $v_{\text{LSR}}$ using the standard solar motion from Schönrich et al. (2010). (d) The $v_{\text{HEL}}$ of the gas is converted to $v_{\text{LSR}}$ using the standard solar motion from Kerr & Lynden-Bell (1986) for all except for L1616, for which we used Mihalas & Binney (1981), since the data is from Maddalena et al. (1986). (e) The four sources with RVs from Kounkel et al. (2017b) were observed with lower resolution compared to APOGEE-2 and have generally larger errors (observational errors between 0.8 to 1.2 km/s). (f) The four sources with RVs from Alcalá et al. (2004) were observed with lower resolution compared to APOGEE-2 and have generally larger errors (observational errors between 2.0 to 2.3 km/s).

References. (1) APOGEE-2 SDSS-DR16; (2) Kounkel et al. (2017b); (3) Alcalá et al. (2004); (4) Nishimura et al. (2015) $^{12}$CO(2-1); (5) Kun et al. (2008) $^{12}$CO(1-0); (6) Maddalena et al. (1986) $^{12}$CO(1-0); (7) Kun et al. (2001) $^{12}$CO(1-0).

a shift of YSO to gas RVs in this region. If anything, they find a slight blue-shift of YSOs in L1630-S suggesting that the shift in Figure 3 is not significant and is likely caused by systematics or erroneous LSR conversion (Appendix B). The other five parameters were then determined from averaging the parameters from the chosen YSO samples. For further details on these regions and sample selection see Appendix A.4 and Fig. A.3.

For L1622 we used the $v_{\text{LSR}}$ of 1.17 km/s as reported in Kun et al. (2008), which is converted to $v_{\text{HEL}} \sim 17.96$ km/s, using the KL86 standard solar motion. Compared to YSO velocities (average $v_{\text{HEL}} = 19.3 \pm 1.2$ km/s, Kounkel et al. 2017b), we find that the latter are relatively red-shifted ($\sim 1.3$ km/s). This might not be significant since inherent systematics of the observations, small-number statistics, or LSR conversion errors could be responsible for this shift. For our analysis, we used gas radial velocity, and the other parameters were obtained from averages of the YSO sample. The position $(l, b)$ was adjusted according to high column-density in L1622 (Appendix A.4 and Fig. A.3).

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Galactocentric coordinate systems that points toward Orion. For the latter, the \( x' \), \( y' \), and \( z' \) are Heliocentric Galactic Cartesian coordinates, and \( X'_{\text{Orion}}, Y'_{\text{Orion}}, Z'_{\text{Orion}} \) are transformed Cartesian coordinates with the \( x' \)-axis pointing toward a central position in Orion at \((l, b) = (206.20^\circ, -22.08^\circ)\). The last three columns are Galactic Cartesian velocities relative to the LSR.

### 3.2.3. 6D parameter determination for the outlying clouds

For the two star-forming cometary clouds, L1616 and IC2118, we used the YSO samples as defined in Sect. 2.3.3. To obtain radial velocities we used the gas velocities from CO observations as reported by Maddalena et al. (1986) and Kun et al. (2001) for L1616 and IC2118, respectively, given in Sect. 2.3.3 and Table 2. For L1616 the radial velocities of YSOs as reported by Alcalá et al. (2004) are consistent with the CO velocities by Maddalena et al. (1986) within the errors, and we used the gas \( v_{\text{LSR}} = 7.7 \) km/s, which is \( v_{\text{HEL}} = 22.6 \) km/s. For IC2118 only gas RVs are available. Based on the findings for the other clouds in our sample, we assumed that YSOs also share on average similar motions as the gas of the associated molecular cloud. Future investigations are needed to confirm this assumption. The other parameters were again determined from average YSO parameters. A more detailed description is given in Appendix A.4 and Fig. A.4.

### 3.3. Galactic Cartesian coordinates and Galactic orbit estimation

We used the Python package Astropy (Astropy Collaboration et al. 2013, 2018) to calculate Galactic Cartesian coordinates, which were used to visualize our results in 3D. In Table 3 we show the resulting coordinates given Heliocentric (\( X, Y, Z \)), Galactocentric (\( X', Y', Z' \)), and also transformed into a coordinate systems that points toward Orion. For the latter, the \( x' \)-axis \( (X'_{\text{Orion}}) \) points toward a central position in Orion at \((l, b) = (206.20^\circ, -22.08^\circ)\). The choice of this position is elaborated be-

| Sub-region | pc | Y | Z | \( X' \) | \( Y' \) | \( Z' \) | \( X'_{\text{Orion}} \) | \( Y'_{\text{Orion}} \) | \( Z'_{\text{Orion}} \) | \( U_{\text{LSR}} \) | \( V_{\text{LSR}} \) | \( W_{\text{LSR}} \) |
|------------|----|---|---|-------|-------|-------|----------------|----------------|----------------|-------------|-------------|-------------|
| L1647      | -368.91 | -251.58 | -161.05 | -8491.30 | -251.58 | -139.31 | 470.20 | 62.85 | 16.94 | -4.40 | -1.64 | -0.57 |
| L1641-S    | -346.94 | -225.52 | -144.55 | -8469.29 | -225.52 | -122.86 | 435.07 | 49.18 | 20.5 | -5.98 | -0.87 | -0.40 |
| L1641-C/S  | -328.35 | -203.39 | -134.76 | -8450.67 | -203.39 | -113.12 | 406.88 | 37.52 | 19.63 | -7.56 | -0.68 | 0.02 |
| L1641-C    | -314.08 | -187.97 | -129.74 | -8436.38 | -187.97 | -108.14 | 386.82 | 29.99 | 16.9 | -8.19 | -0.96 | -0.62 |
| L1641-N    | -316.67 | -183.81 | -130.5 | -8438.98 | -183.81 | -108.89 | 387.56 | 25.12 | 16.38 | -10.29 | -1.06 | 0.03 |
| OMC-4/5    | -323.84 | -182.97 | -132.69 | -8446.15 | -182.97 | -111.06 | 393.99 | 21.2 | 16.63 | -11.12 | -1.80 | 0.31 |
| OMC-1      | -333.12 | -184.97 | -134.47 | -8455.43 | -184.97 | -112.81 | 403.19 | 18.89 | 18.45 | -11.12 | -1.80 | 0.31 |
| OMC-2/3    | -318.31 | -174.33 | -126.5 | -8440.61 | -174.33 | -104.89 | 383.54 | 15.88 | 19.07 | -12.10 | -2.32 | 0.29 |
| L1630-S    | -343.30 | -167.32 | -109.67 | -8456.56 | -167.32 | -88.02 | 387.54 | 2.53 | 38.89 | -11.95 | -0.78 | -0.04 |
| L1630-N    | -376.60 | -177.61 | -105.55 | -8499.84 | -177.61 | -83.78 | 425.45 | -6.9 | 58.69 | -11.11 | 0.31 | -1.06 |
| L1622      | -300.02 | -138.41 | -69.65 | -8422.17 | -138.41 | -88.02 | 322.65 | -8.27 | 59.62 | -4.55 | 0.83 | 10.26 |
| L1616      | -325.71 | -141.62 | -163.36 | -8448.10 | -141.62 | -141.72 | 390.11 | -16.73 | 18.02 | -7.00 | 1.92 | -1.77 |
| IC2118     | -236.15 | -117.12 | -128.23 | -8358.45 | -117.12 | -106.82 | 292.47 | 0.83 | -19.73 | 1.30 | 2.14 | 0.67 |
| Orion X    | -269.79 | -132.77 | -122.03 | -8392.08 | -132.77 | -100.54 | 324.51 | 0.02 | -0.01 | -5.05 | 2.93 | 0.65 |

**Notes.** \( X, Y, Z \) are Heliocentric Galactic Cartesian coordinates, \( X', Y', Z' \) are Galactocentric Cartesian coordinates, and \( X'_{\text{Orion}}, Y'_{\text{Orion}}, Z'_{\text{Orion}} \) are transformed Cartesian coordinates with the \( x' \)-axis pointing toward a central position in Orion (toward \( l, b = 206.20^\circ, -22.08^\circ \)). The last three columns are Galactic Cartesian velocities relative to the LSR.

### 4. Results

In this section we present the resulting 6D parameters for the selected molecular clouds in Orion, and the 3D space motions of these clouds.

#### 4.1. Galactic Cartesian representation of the clouds 3D orientation and motions

In Table 2 we present the resulting 6D parameters \((a, \delta, \varpi, \mu_\alpha, \mu_\delta, v_{\text{HEL}})\) for each sub-region, as determined from average properties of YSOs and gas. The distances \( d \) to the clouds, as determined from YSOs, mostly agree with other studies based on other methods, for example by Zucker et al. (2019a, 2020). We find the largest discrepancy for L1622, where we get \( d = 338 \pm 11 \) pc, compared to Zucker et al. (2020) \( d = 418 \pm 20 \) pc, a difference of 80 pc. This could be due to the fact that L1622

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covers a rather small solid angle in the sky, and is projected on more distant clouds likely associated with the Orion B cloud. This overlapping-cloud scenario would be consistent with gas RV measurements, where L1622 shows a blue-shifted motion relative to its surroundings, suggesting it is a different cloud. Towards IC2118 Zucker et al. (2020) determined distances to three sub-regions \((328^{+15}_{-25}\, \text{pc}, 273^{+18}_{-11}\, \text{pc}, 283^{+16}_{-10}\, \text{pc})\), which scatter around our distance determination of \(d = 293 \pm 14\, \text{pc}\). On the other hand, their distance for L1616 fits very well with ours \((392^{+5}_{-4}\, \text{pc}, \text{and we find} 391^{+12}_{-8}\, \text{pc})\). For Orion A and B a comparison is not straightforward since they report several positions which deviate from the projected high-column-density regions of the clouds, so the Zucker et al. (2020) distances in these regions scatter around our findings. In conclusion, we find that estimating distances to molecular clouds based on YSO distances delivers consistent results, within the errors, when compared to other methods. This was already demonstrated in Groschedl et al. (2018).

In Table 3 we present the Galactic Cartesian representation of the average cloud parameters, as introduced in Sect. 3.3. The Cartesian LSR velocities in the table deliver some first results for Orion. First, the current dominating motion is in the X-direction \((U_{LSR})\), which is mostly negative. Hence, the clouds move away from the Galactic center, except for IC2118. Second, all the motions in Z-direction \((W_{LSR})\) are close to zero, except for L1622, which moves toward the Galactic plane with relative high velocity. \(W_{LSR} \sim 0\, \text{km/s}\) means, that most of the clouds in Orion have reached their maximum distance to the Galactic mid-plane (with distances between 80 to 140 pc from the plane), where they now have slowed down to zero vertical velocity and will consequently not move further away but rather start to fall back toward the plane.

The clouds that clearly show peculiar motions, especially L1622 and also IC2118, could be a result of external perturbations that accelerated some parts of Orion away from the bulk motion of the region. This finding hints at external perturbations acting in the region, as was suggested in Paper I where we attributed the bent structure of the Orion A cloud to be shaped by feedback of massive stars. The diverting motions suggest that external perturbations are very likely and have influenced other parts in addition to Orion A. We investigate this idea further in the following section, where we look at the relative motions of the molecular clouds in Orion in more detail.

4.2. Relative space motions of molecular clouds in Orion

To test the assumption that some of the clouds in Orion were potentially pushed by some feedback event that took place roughly in-between the studied clouds, we first determine the point in time when the sub-regions were closest. To this end, we traced the orbits back and forth in time to determine the moment where the regions show the most compact configuration, hence we calculated the sum of all Cartesian distances between all regions at each time-step to find the minimum. The result is shown in Fig. 4, where we plot the normalized summed distances versus time (for \(\pm 20\, \text{Myr}\), first using all 13 sub-regions, and then using only 9 regions. The second version excludes the last four regions in the Tail of Orion A, since the Tail is — as shown in Paper I — at larger distances than the Head, and is likely unperturbed by the feedback event. The minimum lies at \(-6.2\, \text{Myr}\) and \(-6.7\, \text{Myr}\) when using 13 or 9 regions, respectively, while it is more pronounced when using only 9 regions, without Orion A’s Tail. We conclude that the sub-regions were closest about 5 to 7 Myr ago. Due to the various uncertainties involved, a more precise estimate is not feasible at the moment. The uncertainties include measurement errors, LSR conversion inconsistencies, systematic offsets in the different data sets, and the neglected gravitational field of the gas clouds.

To investigate the situation in more detail we further investigated the clouds’ relative motions. To this end, we defined a central position to derive relative motions between the regions. However, a clear determination of such a central point of origin is not straightforward due to different reasons: (a) There is likely not a single point of origin in the first place. Several massive stars formed in the region and produced feedback (radiation, SNe, winds), as indicated by the nested shells in the Orion-Eridanus superbubble (Ochsendorf et al. 2015; Joubaud et al. 2019, see also the Discussion in Sect. 5.2). More likely, the origin of such feedback could have resided in one or several relatively older stellar group(s), which are located throughout the larger Orion complex, like the OB-associations called Orion.
OB1 (e.g. Blaauw 1964; Brown et al. 1994); (b) If choosing one of the older clusters in the region, then also the age of this progenitor cluster needs to fit into our picture, and should have at least an age of about 10 Myrs to allow for stellar feedback in the form of SNe, and to fit the ages of the presented YSO samples, which are all younger than 5 Myrs. Determining cluster ages is again not free of uncertainties, as elaborated below. (c) Taking a simple average position and motion from the studied clouds (as observed today) would be biased by the chosen cloud sample. Moreover, the studied molecular clouds had different initial masses and densities and therefore were likely influenced differently by a feedback event. A momentum analysis could help, even if it brings further significant uncertainties, especially due to the unknown initial masses and densities; (d) Finally, even if finding the proper progenitor cluster, the uncertainties in the determined 6D cloud parameters do not allow a perfect analysis, since the errors will grow with each time-step.

Considering the above mentioned caveats, we still attempted to identify possible progenitor clusters, that could have been the hosts of massive stellar feedback, in the form of radiation, winds, and supernovae. There are several studies who did a cluster analysis in the Orion region, including Kounkel et al. (2018); Kounkel & Covey (2019), Zari et al. (2019), Kos et al. (2019), and Chen et al. (2019). All of these studies deliver partially overlapping results and overall rather complex stellar groups and sub-groups. For our purposes, we investigated the 25 co-moving groups of young stars in Orion that were recently identified by Chen et al. (2019)8, to get the most reasonable central position, and subsequently relative cloud motions. The authors selected the individual stellar populations by applying machine learning methods to Gaia DR2 astrometry, while many of these represent well-known clusters. By comparing the positions and motions of the individual populations to the cloud ensemble, we identified Orion X (Bouy & Alves 2015) as a possible point of origin for the feedback scenario. It is located roughly between the ONC and the outlying clouds, extending for about 7\degree (\sim 40 pc), as shown in Fig. 5. We investigated the age of Orion X by comparing with isochrones in an Gaia color-absolute-magnitude diagram (CMD, equivalent to an Hertzsprung-Russel Diagram, HRD), as shown in Fig. 6. We used PARSEC isochrones from (Bressan et al. 2012) with the Weiler (2018) Gaia DR2 pass-bands, solar metallicity (metal fraction $z = 0.0152$), and neglected extinction. From the investigated isochrones we determined that the cluster age is likely between 8 and 15 Myr. Due to the scatter of the cluster members in the CMD-space, the uncertain metallicity, systematic errors intrinsic to theoretical isochrones, and possible foreground extinction9, we were not able to determine a more precise age. The given lower limit could

8 The latest version of the sources table was provided via private communication. This reference will be updated as soon as the paper appears in the literature.
9 Unheeded extinction would make the stars seem slightly too young.
Fig. 7. Nine time-snaps showing the relative motions of the sub-regions in $Y'_{\text{Orion}}$ vs $Z'_{\text{Orion}}$ from -6.7 to 6.7 Myr. This projection represents a face-on view of Orion as viewed from the Sun. The x-axis of the coordinate system points toward \( l/b = (206.20^\circ, -22.08^\circ) \). This is the average position of the cluster Orion X (Chen et al. 2019). Its extent is shown by the red disk in the center. The 13 sub-regions are shown as filled circles (colored as in Fig. 1) and labeled in the last panel. The symbol sizes are scaled with distance (along the 3rd axis) and are normalized relative to the red open circle given in the central panel (circle size normalized for Orion X). Larger points are in-front and smaller points in the back of Orion X, to give an impression of depth. The symbol sizes are scaled for each projection individually and are not comparable between Fig. 7 to 9. See text for more information. A movie version is available online at https://homepage.univie.ac.at/josefa.elisabeth.grossschedl/figure7-YZ-orion-timelapse.mp4.

signify a problem for the proposed scenario, while an older age than 8 Myr seems more likely.

For above mentioned reasons we chose the average position and motion of Orion X (see last row in Tables 1 to 3), to determine the relative motions for our cloud sample. To this end, we put the average position of Orion X in the center of our Cartesian coordinate frame, and we individually calculate the average orbit of the cluster the same way as for the sub-regions. The x-axis ($X'_{\text{Orion}}$) of this frame is oriented towards the average Orion X position ($l, b = 206.20^\circ, -22.08^\circ$), as given in Sect. 3.3 and Table 2, which allows a better orientation and interpretation of the situation.

The results are presented in Figs. 7 to 9 which show the positions of the sub-regions at several snapshots in time, while the central panels in each Figure represent the situation today. Figure 7 shows the view in $Y'_{\text{Orion}}/Z'_{\text{Orion}}$ coordinates that approxi-
Fig. 8. Nine time snap-shots showing the relative motions of the sub-regions in $X'_{\text{Orion}}$ vs $Z'_{\text{Orion}}$ from -6.7 to 6.7 Myr. This projection represents a side view of Orion. See Fig. 7 and text for more information. A movie version is available online at https://homepage.univie.ac.at/josefa.elisabeth.grossschedl/figure8-XZ-orion-timelapse.mp4.

mates our view at $t = 0$ Myr\textsuperscript{10}, hence it presents a face-on view. Figure 8 ($X'_{\text{Orion}}/Z'_{\text{Orion}}$) shows a side-view within this coordinate frame, revealing the different distances of the sub-regions relative to the Sun. Especially, the prominent Tail of Orion A is clearly visible. Figure 9 ($Y'_{\text{Orion}}/X'_{\text{Orion}}$) shows a top-down view and highlights again the bent structure of Orion A’s Head. This last orientation is similar to Fig. 4 in Paper I. The sub-regions are colored as in Fig. 1. The point-sizes are scaled with distance within the current projection (i.e. along the 3rd axis), and they are normalized relative to Orion X (light-red open circle in middle panels). The larger red “disk” in the center of each panel represents the location and extent of Orion X, which we determined to be about 40 pc (from known members, and for the situation today). The relative trails of the regions are shown as gray lines. Each figure shows nine snap-shots in time between -6.7 and 6.7 Myr. The starting-time was chosen based on the minimum distances between the regions as demonstrated in Fig. 4. The analysis of the cloud’s 3D space motions, as shown in Figs. 7 to 9, reveal that the clouds indeed were closest about 6 Myr ago. This supports the idea that some feedback event(s) took place located near the Head of Orion A, and in-between the studied regions, since all sub-regions move radially away from a rough common center. However, they do not seem to converge to a central point. This could be due to uncertainties, or indicate

\textsuperscript{10} The Sun moves away from that point of view with time.
that there was not a single event that shaped the regions. Additionally, the small clumps L1622, L1616, and IC2118, seem to pass each other when starting at -6.7 Myrs. This indicates that this starting time is likely too early and a possible trigger (at least for these three regions) could have happened slightly later.

For individual regions we see that especially the small cometary clouds show quite high relative motions. This is feasible, since the lower mass clouds were likely affected differently compared to their high-mass counterparts in the region. L1622 is located closest to the Galactic plane and at the same time continues to move toward the plain at high speed. This indicates that L1622 originates from the same region as IC2118 and L1616, even though it can be found today in a completely different environment, and actually was added in this paper to the Orion B clouds. For Orion A we see that the Head of the cloud indeed seems to relatively approach the Tail, supporting the scenario in Paper I, where we already argue that the Head of the cloud was pushed. The relative motions of Orion A’s Tail also show a motion departing from Orion X, which opposes our argument that the Tail is largely unperturbed, which we made based on the facts that it is more distant and a more quiescent star-forming region. Likely the Orion X cluster has some relative motion on its own and did not influence the Tail as strongly as indicated in Figs. 7 to 9 (see also Sect. 5.1 and Fig. 10). The Orion B clouds (L1630-
S/N) also move away from the central position, while L1630-S fits better in this scenario, with Orion X as center. The overall location of L1630-N is a bit off from the center. It could be that some parts in Orion B were rather influenced by feedback originating from different cluster besides Orion X.

Other possible progenitor clusters include groups with ages of about 10 Myr or older which are found near the belt stars of Orion, or the Orion Belt Population (OBP; Kubiak et al. 2017) in Chen et al. (2019) or Orion D in Kounkel et al. (2018), or even the associations found further North-East in OB1a (Warren & Hesser 1977; Briceño et al. 2001). To further understand the role of feedback in the whole region, all groups in Orion need to be studied in more detail in that context, implying first a more robust and more statistically significant membership analysis followed by better age determinations. In Sect. 5.3 we briefly discuss some groups in the context of the feedback scenario, however a more detailed study of all groups in Orion goes beyond the scope of this paper.

5. Discussion

In the following we discuss the implication of the found radial motions in-printed in our studied cloud sample. In our study on the 3D shape of Orion A (Großschedl et al. 2018) we found that this cloud is twice as long as previously assumed with a peculiar bent Head. We suggested then that the cloud was perturbed by external forces, likely feedback forces from massive stars. We argued, if such a feedback event happened in the recent past in Orion, which was likely given the number of massive stars in the region, it must have left a signature in the observed motions of the youngest stars and the gas from where they are emerging. In this paper we attempt to put Orion A in context by exploring, for the first time, the 3D dynamics of the Orion star-forming complex by combining gas line-of-sight motions with space motions of YSOs. Very recently, Rezaei Kh. et al. (2020) using a different approach, Gaussian Processes-based, confirmed the overall shape of Orion A, further motivating the analysis in this paper.

5.1. Signatures of feedback in the large scale radial velocity structure

Our results indicate that a major feedback event took place in Orion about 6 Myr ago. If the regions investigated in this paper were indeed perturbed by a large feedback event, one could expect, to zero order, a roughly bimodal velocity distribution for the gas and young stars in the complex: stars and gas not affected by the feedback event moving at a primordial radial velocity, and the perturbed gas (and the young stars associated with it) moving at a different radial velocity. In Fig. 10 we present a Position-Velocity-Diagram (PV-Diagram) for the region. The grey background dots are all APOGEE-2 sources with applied quality criteria. The 13 sub-regions are shown as filled circles and colored as in Fig. 1, and the average PV-position of Orion X is shown in red. For the 13 sub-regions the gas $v_{LSR}$ was used. The predicted velocities (box symbols) are the expected velocities from Galactic rotation alone, without external pressure from a feedback event, calculated for each sub-region individually using a Milky Way potential (Bovy 2015), with the help of Astropy and galpy\footnote{galpy.potential.MWPotential2014, galpy.potential.vcirc}. The predicted velocities are a function of $d$ and $b$ and they fall at $v_{LSR}$ about 5 to 7 km/s for stars in Orion.
It is clear from Fig. 10 that the observed radial velocities present a bimodal distribution (see histogram on the right y-axis) and that most stars in Orion are located above the predicted velocities. Most stars seem to form an arc-like structure above about 5 km/s, except for IC2118 and L1622. This shows that most young stars in Orion have relatively red-shifted line-of-sight motions with regards to average motion of the stars and gas in the region. This supports the feedback-driven "push scenario", where an external feedback event took place largely in-front of pre-existing gas, from the Sun’s point of view. The clouds in the region also largely follow this arc. Only the cometary clouds L1622 and IC2118 have blue-shifted velocities and are moving relatively to the front, indicating that they were located between the feedback event and the Sun and that only a small fraction of the gas was on "our" side of the event. L1616 seems unperturbed in this PV-space, since it has only a minor component of motion along the line-of-sight direction.

The position of Orion X in this PV-Diagram indicates that the cluster roughly shares the large scale motion of unperturbed regions in Orion, showing slightly blue-shifted velocities. We note that only three stars in Orion X have been observed by APOGEE-2 with sufficient quality, hence the average $v_{LSR}$ of the cluster is likely more uncertain than the scatter of the observed data points (error-bar of scatter fits within the shown red circle). Note that the predicted velocities in the PV-Diagram are an approximation, as we know Orion is part of the Radcliffe Wave, itself deviating slightly from pure Galactic rotation (Alves et al. 2020) (it is interesting that the Tail of Orion A appears slightly blue-shifted in comparison with the average rotation). In general, assuming a simple Galactic rotation for any single cloud is always an approximation, since various forms of gravitational or feedback forces constantly act within the Galaxy as shown recently inJefferson et al. (2020) via numerical simulations.

Still, the point we want to make here is that the deviation caused by feedback (of the order of 10 km/s, +5 and -5 km/s from the average) dominates the velocity distribution in the Orion complex, revealing that feedback has a major impact on the gas dynamics of the entire complex, and subsequently on the velocities of the young stars formed inside this perturbed gas, hence most of the young stars in Orion.

We have now several lines of evidence (spatial and dynamical) that Orion A’s Head — also known as the Integral Shape Filament — clearly seems to have been pushed backwards while the Tail seems dynamically unperturbed, confirming our assumption of a compressed Head (Paper I) and a largely unperturbed Tail. We also know that the star formation rate in the Head of Orion A is about an order of magnitude higher compared to that of the Tail (Großschedl et al. 2019b). Together, these facts naturally lead to the conclusion that practically all of the very young stars (Class I and II) in the star formation rich Head of Orion A, but also in Orion B, and possibly some of the young but dust-free populations like the OBP (Kubiak et al. 2017, see also Sect. 5.3.), are a product of large-scale triggering in Orion. This conclusion implies that at the genesis of the Orion Nebula Cluster (and NGC2023/2024 in Orion B) lies a feedback/compression/trIGGERing process, which will need to be taken into account in cluster formation models.

We caution against a “one-event-fits-all” feedback event scenario, and address this further below. For example, the situation in the Orion B main cloud seems more complex than Orion A. Our determined relative motions of the two main parts in Orion B (especially L1630-N) do not fit perfectly in the picture with Orion X as progenitor. Still, there are clearly perturbations visible in the radial velocities of the gas in Orion B going beyond the shown PV-Diagram in Fig. 3. Additionally, the proper motions of our studied YSO samples in Orion B do not show a clear single peak in proper motion space, suggesting further perturbations and indicating a more complex dynamical status than a “simple” push from the “front” for these regions. Finally, the HII-region, that illuminates the Horse Head Nebula (IC 434) is likely to be a significant influence on the Southern part of the cloud (see also Bally et al. 2018; Orkisz et al. 2019).

Concluding, feedback in Orion, and, in particular, the feedback event that took place about 6 Myr ago, has had a fundamental role in shaping the gas distribution and gas dynamics, and consequently, the dynamics of the young stellar population in Orion.

5.2. Coherent radial cloud motions in Orion on the 100 pc scale

A main result of this paper is the surprising discovery of coherent radial cloud motions on 100 pc scales in the Orion complex. We argue that the best explanation for the observables today calls for a major feedback event that took place in Orion about 6 Myr ago, that we name from here on the Orion—6 event. This feedback event shaped the distribution and kinematics of the gas we observe today in two fundamental ways. First, it accelerated gas clouds radially away from a region we tentatively associate with the Orion X stellar population, and second, it compressed these clouds, increasing their star formation rate. The Head of Orion A, containing the Orion Nebula Cluster, is a good example of the latter, as it displays today a star formation rate about an order of magnitude higher than the unperturbed Tail region (Großschedl et al. 2019b).

The feedback-driven scenario we propose here for Orion is comparable to the classical model of Elmegreen & Lada (1977), in that a previous generation of stars has a significant impact on the formation of the next. Given that the Orion complex is part of the much larger Radcliffe Wave gas structure (Alves et al. 2020), there is no implicit need in our scenario to “collect-and-collapse”, but only to “shape-and-collapse” the pre-existing gas in the complex.

The idea that the Orion clouds were and are being affected by the feedback of massive stars is not new (e.g., Bally et al. 1987; Bally 2008). It has been proposed that several nested shells are superimposed along the line-of-sight, forming the so-called Orion-Eridanus superbubble, a less than 10 Myr old relic shell of several Supernovae remnants, spatially encircling the main Orion clouds (e.g., Lee & Chen 2009; Pon et al. 2014b,a, 2016; Ochsendorf et al. 2015; Soler et al. 2018; Joubaud et al. 2019). The progenitors of the superbubble are likely related, at least partially, with the Orion—6 event presented in this paper. A similar finding is discussed in Kounkel et al. (in prep., private communication) who use a different approach by investigating the 3D dynamics of stellar groups from Kounkel & Covey (2019). They attribute the large scale dynamics of these young clusters to feedback from massive stars, also tracing this back to roughly 6 Myr ago, independently confirming the main results of this work. Another very recent result by Rezaei Kh. et al. (2020) confirmed the bent structure of Orion A, using a Gaussian processes-based method to estimate the 3D structure of dust, via extinction. Additionally, they identify with their method a foreground dust ring, seen in projection in-front of Orion A, and partially Orion B, and they suggest that some of the closer YSOs toward Orion A are part of the foreground-ring. They determine the center of this ring to be roughly at a distance of 350 pc, and argue that it could be a remnant of previous star formation episodes in this region.
The location of this dust structure lies in the vicinity of Orion X, and could be another signature of feedback connected to the Orion–6 event.

While Orion X is likely one of the progenitor stellar populations of the Orion–6 event, we cannot exclude the possibility that there were other populations contributing to the proposed scenario. From momentum conservation considerations alone, one would expect that the smaller clouds (like L1622, L1616, IC2118) move faster than the more massive clouds. This is true to a point, L1622 is the fastest moving cloud, but the more massive Orion A and B clouds seem to be moving too fast if all sub-regions were affected by a single event. More likely, several events, and the continuous forces from radiation and stellar winds from massive stars, have instead been shaping the Orion complex. A more detailed discussion of this event, or events, is critical and starts by identifying the complete population of Orion X, and possible other progenitor groups, which urgently warrants a dedicated study. Orion X is a poorly understood stellar group, only recently identified in the Hipparcos data (Bouy & Alves 2015), and an estimate of its initial mass function is needed to confirm its capability of delivering massive stellar feedback.

Regarding the source of feedback behind the Orion–6 event, much remains to be understood. Supernova(e) from the Orion X population are obvious culprits, e.g., Bally (2008) estimates 10 to 20 Supernovae have exploded in the Orion complex over the last 12 Myr, but so are winds, photo-ionization, and mass loss from evolved massive stars in the region. Figuring out the relative roles of these sources of feedback in Orion is critical to quantify, to understand the role of feedback in driving star formation, a critical missing piece in our understanding of star and molecular cloud formation, with far-reaching impact beyond the Local Milky Way.

We know from simulations (e.g., Chevalier 1999; Kim & Ostriker 2015; Seifried et al. 2018; Lucas et al. 2020) that supernovae (SNe) are potentially able to shape pre-existing molecular clouds when happening in the vicinity (within few 10 pc). This distance criterion means that it is very unlikely for one single SN to shape an entire large scale region like Orion which was probably already filled with molecular gas structures. Further analysis and simulations are needed to investigate the triggered star formation scenario in the context of Orion as presented in this paper. The complexity of such simulations go beyond the scope of this work, where we focus on the observational signatures. In a future paper (G. Herbst-Kiss et al. in prep.) we will present SPH simulations to investigate numerically the possible origin of the observed shape and dynamics for Orion A, and finally for the whole Orion region.

5.3. Other stellar groups in the context of the feedback scenario

There are other over-densities visible in the PV-diagram, marked in Fig. 10. Most of them are known groups and are listed in Chen et al. (2019). The oldest sub-group in the Orion OB-association is OB1a (e.g. Blaauw 1964; Brown et al. 1994; Briceño et al. 2007a,b), which is part of a large structure called Orion D in Kounkel & Covey (2019). OB1a can be split up into further sub-groups, as was done for example by Kos et al. (2019) or Chen et al. (2019). The oldest subgroup is ASCC20 (Kharchenko et al. 2013) and has an age of about 21 Myrs as reported in Kos et al. (2019). Its location, however, largely to the West of our discussed clouds, does not fit into the scenario proposed here. Still, due to its age it could have been one of the first clusters in Orion producing significant feedback and potentially triggering star formation. It overlaps in the PV-space with the subgroup OBP-West (Kubiak et al. 2017; Chen et al. 2019), which is part of Blaauw’s OB1b population (e.g. Warren & Hesser 1978; Briceño et al. 2005). The OB1a population also contains other prominent subgroups, like 25 Ori (Briceño et al. 2007b), but better named Briceno-1 (also called ASCC16, Kharchenko et al. 2013; Kos et al. 2019), as the star 25 Ori is not part of the cluster (Chen et al. 2019). The line-of-sight velocities of this group largely follow the average predicted velocities assuming Galactic rotation, as can be seen in Fig. 10, which could mean that OB1a, and Briceno-1 in particular, did not experience any significant perturbation prior to formation. It was long thought to be one of the oldest groups in Orion, however Kos et al. (2019) report that ASCC16 (about 13 Myr) is younger than ASCC20. A dedicated study of the ages of all Orion groups is clearly warranted, and will enlighten the star formation history as well as the role of stellar feedback in the region.

Several groups have been identified along the line of sight in the region surrounding the Orion Belt Stars. Additional to the mentioned OBP-West, there are further groups listed in Chen et al. (2019), while the stellar members of three of these groups share approximately the same PV-space (OBP-d, OBP-b, OBP-far), and fall within the arc-like structure in the PV-Diagram, above NGC 2068/2071 (L1630-N). Only one of the OBP groups seems to follow average Galactic rotation, being located in the blue band in Fig. 10, the OBP-near group (Chen et al. 2019). Besides Orion X it is also a promising candidate for feedback in this region, being roughly 10 Myr (from an isochrone investigation). Since the OBP groups are located closer to Orion B, they are likely better candidates for hosts of feedback acting on Orion B, but it is too early to make a more solid statement.

Another very prominent group in the PV-Diagram is the cluster σ Orionis (e.g., Caballero 2010a; Caballero et al. 2010b; Hernández et al. 2007; Caballero et al. 2019). It is located above NGC 2023/2024 (L1630-S) in PV-space. This rich young cluster (about 2 - 4 Myr) is well-known for the massive O-star at its center giving it its name. The cluster still contains pre-main-sequence stars with circumstellar disks (Class II YSOs, see also Fig. A.3), while the molecular gas out of which the stars have formed has already been dissolved. Being located between Orion A and B, it is an interesting object, and it might also be a result of the massive feedback event that took place about 6 Myr ago.

Focusing on Orion A, the region surrounding the ONC (mean age ~ 2.5 Myr, e.g., Jeffries et al. 2011) is the most prominent in the PV-Diagram. Along the same line-of-sight, the ONC region is superimposed with the older NGC1980 cluster (4-5 Myr, Alves & Bouy 2012), proposed to be in the front of the ONC in Alves & Bouy (2012) and Bouy et al. (2014), and was recently identified as a likely separate group from the ONC (Chen et al. 2019). In PV space, NGC1980 is virtually identical with the ONC (Da Rio et al. 2016), which together with the estimated distance between these two clusters (of the order of 10 pc) has made the separation of populations difficult. Better astrometric data from Gaia in the near future will hopefully clarify the nature of these two fascinating clusters. In this paper we are not focusing on the stellar clusters in Orion but on the 3D dynamics of molecular clouds, we will defer the disentangling of the various proposed stellar groups for a future paper.
5.4. Implications for the cloud-cloud collision scenario for the Orion complex

Several recent papers have argued for a cloud-cloud collision scenario for the formation of the ONC (Fukui et al. 2018; Lim et al. 2020), NGC2023 (Yamada et al. 2020), NGC2024 (Enokiya et al. 2020), and NGC 2068/2071 (Fujita et al. 2020) in the Orion complex. The cloud-cloud collision argument is made based on the analysis of the radial velocity of the CO gas, in particular a jump in the velocities at particular star-formation rich regions, like the Head of the Orion A cloud. We note that the scenario we propose here naturally explains the CO observables in Orion A without the need for a second molecular cloud being involved. The mechanical feedback-driven scenario presented here is still technically a collision, likely a shock, between an existing molecular cloud and a feedback flow of atomic/ionized hydrogen. We cannot rule-out the cloud-cloud collision with the present data, but argue, given the dynamical status of the clouds studied here, that even in the case of a collision of two molecular clouds, the driver behind this collision is likely the stellar feedback forces.

6. Summary

We were able to measure for the first time the 3D space motions of molecular clouds in the Orion star-forming region, using the 3D space motion of the YSOs as a proxy for the motion of the gas. The main results of this work are as follows:

1. We confirm that radial velocities of YSOs and that of the hosting molecular clouds are essentially the same, as recently found in the literature. Therefore, YSO’s proper motions can be used to reasonably estimate their parental cloud’s 3D motions.

2. We report the discovery of coherent radial cloud motions on 100 pc scales in the Orion complex. We argue that the best explanation for the observables is the existence of a major feedback event that took place in Orion about 6 Myr ago. This feedback event, that we name the Orion–6 event, shaped, in part, the distribution and kinematics of the gas we observe today. The dynamics of the young stars in Orion carry the memory of its feedback-driven star formation history.

3. We associate the origin of the Orion–6 event to the Orion X population, recently identified by Bouy & Alves (2015) and Chen et al. (2019). We also argue that Orion–6 is unlikely to be the only major feedback event in the region, and that feedback processes over the last 10 Myr (supernova explosions, radiative-pressure, photo-ionization, mass-loss, and the continuous forces from stellar winds from massive stars) have been shaping the gas distribution, gas dynamics, and the star formation rate in the Orion complex.

4. We argue, based on kinematics, that the majority of the young stars in Orion are a product of large-scale feedback-driven triggering, that can raise the star formation rate in a cloud by about an order of magnitude, as in the case of the Orion A’s Head (the Integral Shape Filament). Our results imply that at the genesis of the Orion Nebula Cluster (and NGC2023/2024 in Orion B) lies a feedback/compression/triggering process.

5. We were able to estimate for the first time the 3D dynamics of star-forming molecular clouds on the scale of an entire cloud complex. Such an analysis is a crucial missing piece to understand the formation and dissipation mechanisms of these clouds, their dynamics, and their mass distribution. Similar analysis is and will be available for most nearby cloud complexes with existing and upcoming Gaia data, combined with existing, and upcoming, radial velocity and proper motion surveys.

The new dynamical view of Orion presented in this paper is another example of how Gaia is opening a 3D window not only on the topology (Großschedl et al. 2018) but also the dynamics of the dense star-forming ISM, a critical missing ingredient in our understanding of star formation. In the future, the superior Gaia DR3 data coming in 2021, supplemented by proper motion measurements of embedded sources by the ESO VISIONS Public Survey12, will make the Orion complex a benchmark region to quantify the impact of feedback by massive stars, a fundamental but poorly constrained physical process.

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Appendix A: Detailed description YSO sample selection

In this Appendix we give a detailed description of YSO sample selection. First, we define the quality criteria for Gaia DR2 and APOGEE-2 data, next we explain the YSO selection criteria when using WISE and 2MASS photometry, and then we present the final samples for the sub-regions in Orion B and the outlying clouds, based on position and motion criteria. Orion A is not discussed here separately, because the necessary steps were already explained in the main part of this paper.

Appendix A.1: Gaia quality criteria

We apply the following quality criteria to all our YSO samples:

\[ 200 \text{ pc} < d < 700 \text{ pc}, \]
\[ |\mu_{\alpha*}| < 10 \text{ mas/yr}, \]
\[ |\mu_{\delta}| < 10 \text{ mas/yr}, \]
\[ \text{err}_{\mu_{\alpha*}}, \text{err}_{\mu_{\delta}} < 1 \text{ mas/yr}, \]
\[ e_{u}/\pi \leq 0.1, \]
\[ \text{ruwe} < 1.4, \]
\[ G_{\text{err}} < 0.05 \text{ mag}, \]
\[ \text{visibility periods used} > 6 \]

These conditions select sources within a distance interval enclosing the Orion star forming complex. Moreover, we pre-select sources within a rough proper motion range of ±10 mas/yr. Sources showing larger proper motions either do not belong to the Orion population or have peculiar motions with respect to the average motion and are therefore not needed for our analysis. The latter conditions are quality criteria to reduce contamination by inferior data. For details on the Gaia DR2 parameters see https://geo.esac.esa.int/archive/documentation/index.html or Großschedl et al. (2018).

Appendix A.2: APOGEE-2 quality criteria

For regions that were covered by the APOGEE-2 SDSS-DR16 survey we apply the following criteria:13

\[ 10 \text{ km/s} < \text{VHELIO\_AVG} < 40 \text{ km/s}, \]
\[ \text{VERR/\text{VHELIO\_AVG}} < 0.1, \]
\[ \text{VERR} < 0.2 \text{ km/s}, \]
\[ \text{VERR\_MED} < 0.2 \text{ km/s}, \]
\[ \text{VSCATTER} \leq 1 \text{ km/s}. \]

To get \( \text{VHELIO} \) of the YSOs we use the APOGEE-2 parameter called \( \text{VHELIO\_AVG} \), which is the SNR weighted average velocity as determined from the combined spectra. To get reliable RVs we use the SNR weighted uncertainty \( \text{VERR} \) and the median visit RV uncertainty \( \text{VERR\_MED} \), but they are known to be underestimated. Hence, for some cases VSCATTER might represent a better estimate of the overall measurement precision. If VSCATTER is much larger than VERR\_MED then this could be an indicator that the star is in a stellar binary. Therefore we apply an additional cut using VSCATTER. The first cut includes a rough selection in \( \text{VHELIO} \) space, to pre-exclude outliers with untypical Orion RVs.

Appendix A.3: Selecting additional YSOs with WISE and 2MASS photometry

We select additional YSO candidates to get more robust statistics, on top of the ones from the literature (see Sect. 2). To this end, we apply selections in color–color and color–magnitude diagrams using photometry spanning from the near-to the mid-infrared, including data from the all-sky surveys 2MASS (NIR) and AllWISE (MIR). These data are provided by the NASA/IPAC Infrared Science Archive (Rebull et al. 2018).14

Usually, an infrared based YSO selection tends to be contaminated by extra-galactic sources. Due to the requirement of using sources measured by Gaia we are able to pre-select in distance (see Equ. A.1). This reduces fore- and background contamination substantially (e.g., AGB stars, galaxies, AGNs). Such a Gaia pre-selection might not give the most complete sample of YSOs, since the optical Gaia mission misses the youngest embedded sources, but a complete sample is not necessary for our purposes, while we strive to increase the numbers for good statistics.

Before applying selection criteria in color and magnitude space we apply several quality criteria to the NIR and MIR photometry from 2MASS and WISE, sometimes used in combination. The WISE photometry (W1, W2, W3, W4 at 3.4 µm, 4.5 µm, 12 µm, 22 µm, respectively) is prone to be contaminated by extended emission close to star-forming regions (nebulosities, outflows), especially the two longer wavelength bands W3 and W4. To mitigate this, we include quality criteria that consider extended sources.

\[ w1\text{snr}, w2\text{snr} > 10, w3\text{snr}, w4\text{snr} > 7, \]
\[ w_{\#\text{sig}} < 0.2, w_{\#\text{chi}} < 20, \]
\[ w_{\#\text{mag}} > 0.1, \]
\[ 0 < w_{\#\text{mag}} − w_{\#\text{mag}} < 2 \text{ mag}, \]
\[ w_{\#\text{ce}\_\text{mag}} \neq D, H, O, P, \]
\[ v_{\#\text{sig}}, v_{\#\text{sig}}, v_{\#\text{sig}} < 0.1 \text{ mag} \]

The symbol “#” is a placeholder for a number of the four WISE bands if the condition is equal for all15.

We apply selection criteria within six different color spaces to select sources with infrared excess. The above mentioned quality criteria (Equ. A.3) are applied only to those bands used in the individual selection, while all include the Gaia criteria from Equ. A.1. In some cases we apply a cut parallel to the extinction vector to get rid of sources that are reddened due to foreground extinction, and are therefore located above the main-sequence. For the used reddening law see Meingast et al. (2018) and Großschedl et al. (2019a). The selection criteria are as follows:

a) W123-selection: WISE selection including the bands W1, W2, and W3. The value −4.273 represents the slope of the extinction vector in the W123 color space (see Fig. A.1.a).

\[ W1 − W2 > 0.05 \text{ mag}, \]
\[ W1 − W2 > −4.273 \times (W2 − W3 − 0.7) \]

b) W124-selection: WISE selection including the bands W1, W2, and W4 (see Fig. A.1.b).

\[ W1 − W2 > 0.05, W2 − W4 > 2 \]

14 https://irsa.ipac.caltech.edu/frontpage/
15 For more details on the AllWISE parameters see http://wise2.ipac.caltech.edu/docs/release/allwise/expsup/sec2_1a.html and Großschedl et al. (2019a), for the 2MASS parameters see https://old.ipac.caltech.edu/2mass/releases/allsky/doc/sec2_2a.html

13 Based on the APOGEE-2 tutorial on how to use radial velocities, https://www.sdss.org/dr16/irspec/use-radial-velocities/
Fig. A.1. Six selected color-color diagrams showing the WISE/2MASS selection criteria to get YSOs with infrared-excess. The gray dots in the background are all sources toward Orion B that pass the Gaia quality criteria plus the additional individual WISE and/or 2MASS selection conditions, as given in Sect. A.3 in the sub-points a) to f); the blue lines indicate the selection-borders and the blue dots are the selected YSO candidates from the whole Orion B region as displayed in Fig. A.3; the black dots are known YSO candidates (Megeath et al. 2012, 2016); the magenta dots are the new YSO candidates in the three sub-regions (Fig. A.3), see also the legend on the right. The numbers of selected YSO candidates are given in the respective color in the upper left corner. The black arrows show the extinction vectors, with the length given in the lower right corner in $A_V$ (mag).

Fig. A.2. Four color-magnitude diagrams, showing additional conditions for the selections c) to f). See Fig. A.1 and text for more explanations.

c) JW12-selection: Combined WISE and 2MASS selection including the bands J, W1, and W2. The value 7.2894 represents the slope of the extinction vector in the JW12 color space (see Fig. A.1.c). The latter condition additionally excludes main-sequence sources in the JW2 color-magnitude diagram (Fig. A.2.c).

\[ \begin{align*}
W1 - W2 &> 0.35, \\
J - W1 &< 7.2894 \times (W1 - W2 - 0.2) + 1 \\
J &< 12 \times (J - W2 - 1.1) + 7 \\
\end{align*} \]  
(A.6)

d) HW12-selection: Combined WISE and 2MASS selection including the bands H, W1, and W2. The value 3.2298 represents the slope of the extinction vector in the HW12 color space (see Fig. A.1.d). The latter condition additionally excludes main-sequence sources in the HW2 color-magnitude diagram (Fig. A.2.d).

\[ \begin{align*}
W1 - W2 &> 0.35, \\
H - W1 &< 3.2298 \times (W1 - W2 - 0.25) + 0.6 \\
H &< 10 \times (H - W2 - 0.1) + 6 \\
\end{align*} \]  
(A.7)

e) HKW2-selecton: Combined WISE and 2MASS selection including the bands H, K, and W2. The value 1.2188 represents the slope of the extinction vector in the HKW2 color space (see Fig. A.1.e). The latter condition additionally excludes main-sequence sources in the KW2 color-magnitude diagram (Fig. A.2.e).

\[ \begin{align*}
K - W2 &> 0.58, \\
H - K &< 1.2188 \times (K - W2 - 0.5) + 0.2 \\
K &< 10 \times (K - W2) + 7.7 \\
\end{align*} \]  
(A.8)

f) JHK-selection: 2MASS selection including the bands J, H, and K. The value 1.7473 represents the slope of the extinction vector in the JHK color space (see Fig. A.1.f). The latter conditions are given by:

\[ \begin{align*}
K - W2 &> 0.8, \\
J - K &< 1.7473 \times (K - W2 - 0.8) + 0.2 \\
K &< 10 \times (K - W2) + 7.7 \\
\end{align*} \]  
(A.9)
Fig. A.3. Top: Region selection for the three Orion B sub-regions, L1630-S (red), L1630-N (blue), and L1622 (green). Only those YSOs within the circular selected regions are marked in color if they survive the proper motion selection (bottom). The gray dots in the background are all sources toward the region (with \( \varpi > 1 \) mas), and the black dots are all selected YSOs within the whole displayed region that survive the Gaia quality criteria. For orientation, the three belt stars and \( \sigma \) Ori are marked with yellow star symbols. The dotted lines are extinction contours and outline the clouds of interest. The small cluster of YSOs in the top-right (\( l, b \sim 203.2, -1.2 \)) is not obviously related to any gas, while it lies very close to the cometary cloud L1617. Bottom: YSO proper motion selection for the three Orion B regions. The colored dots indicate the proper motion selection and are the same as in the top panel. The black dots are all YSOs within the individual region selections (from top panel) but are excluded from the final samples by the proper motion cut.

These selections are representatively demonstrated for the Orion B region in Figs. A.1 and A.2. The whole investigated region in these Figures extends beyond the Orion B clouds and includes \( \sigma \) Ori and parts of OBP, as can be seen in Fig. A.3, where the black dots are all selected YSO candidates. The same procedure was done for the region surrounding the outlying clouds (see Fig. A.4), while the detailed color diagrams are not shown explicitly here.

For the three Orion B sub-regions the combined WISE/2MASS YSO selections deliver 136 YSO candidates within the three regions of interest (see Sect. A.4), which include 106 sources (78%) that were previously identified with Spitzer (Megeath et al. 2012, 2016). So we were able to add 30 additional YSO candidates for the three Orion B regions.

For the regions surrounding the outlying clouds we select in total 19 YSOs, from which 14 are located in L1616, and 5 are in IC2118. Of the 14 sources, 11 were already known pre-main-sequence stars as reported in Alcalá et al. (2004), hence, we were able to add 3 additional YSOs for L1616. The five sources in IC2118 were already known YSOs, listed in Guieu et al. (2010). Any additional new WISE/2MASS YSOs in that sub-regions did not make it into the final samples due to our final individual selection criteria for each region (see below, Sect. A.4).
Table A.1. Parameters for selections in position (l, b) and proper motion (μ_x, μ_y) space for Orion B and the outlying clouds.

| sub-region | (x, y) = (l, b) (°) | (x, y) = (μ_x, μ_y) (mas/yr) |
|------------|----------------------|-------------------------------|
| L1630-S    | 206.65 -16.20 0.9 0.6 | 0.4 -0.9 2.4                 |
| L1630-N    | 205.25 -14.15 0.6    | -0.4 -0.8 2.0                 |
| L1622      | 204.70 -11.75 0.6    | 4.9 0.0 1.0                   |
| L1616      | 203.60 -24.60 0.5    | 0.8 -0.85 1.0                 |
| IC2118     | 206.40 -26.00 0.5    | 0.8 -3.4 1.0                  |

Notes. For circular selections applies (x-x_0)^2 + (y-y_0)^2 < r^2 with x_0, y_0 being the center positions of the circle, and r the radius. For L1630-S we select sources within an elliptical region, (x-x_0)^2/a_x^2 + (y-y_0)^2/b_y^2 < 1. The numbers given in l and b are here the semi-major and semi-minor axis, respectively.

Appendix A.4: Description of detailed sample selection for the regions

For Orion A we use the whole region surrounding the GMC as already demonstrated in Großschedl et al. (2018). For the sub-regions within Orion B and the outlying clouds we apply selections as follows. First we select sources within circular (or elliptical) regions, which enclose the cloud parts of interest. Such selections are applied in position (l, b) and proper motion space (μ_x, μ_y), given in Table A.1.

We defined these selections by individually investigating each region to select YSOs that are close to the molecular clouds on sky and that show an over-density in proper motion space. For three regions (L1622, L1616, IC2118) there exists a pronounced peak in proper motion space, with a small scatter of about 0.3 mas/yr (see Figs. A.3 and A.4, bottom panels). For the two regions in L1630-S/N (NGC2023/2024, NGC2068/2071) there is no such typical proper motion peak and the scatter tends to be larger, up to 1 mas/yr. This is also because we allowed a larger radius in proper motion space, due to the lack of a clear peak. For NGC2068/2071 (L1630-N) we find an interesting structure in proper motion space, likely containing two peaks which lie very close together. When separating the elongated PM structure in the middle, the two resulting samples roughly separate in North-South direction. This could be a signature of the two involved clusters. Nevertheless, we kept the two structures combined and used the average motions of all YSOs, since we are interested in the bulk motion of the region, and not the internal dynamics. For NGC2023/2024 (L1630-S) there is also no clear peak in PM-space detectable. The seemingly chaotic motions could be a signature of perturbation. The detailed selections are further demonstrated in Figs. A.3 and A.4.

For Orion B regions the following additional cuts were applied. First, we applied a more stringent distance criterion, after investigating the dominating distances for that regions:

300 pc < d < 550 pc  

(A.10)

Second, for sources observed by APOGEE-2 (in L1630) we apply an additional cut in v HEL, to exclude outliers:

23 km/s < VHELIO_AVG < 33 km/s  

(A.11)

16 We use proper motions, not tangential velocities, since the sources are selected to be close in space, which makes selections in either space virtually identical.

Finally, we apply an additional distance criterion for L1616:

350 pc < d < 440 pc  

(A.12)

The here presented selection approach is rather simple and maybe a clustering algorithm would deliver a more robust cluster selection. However, for our purposes this basic approach is sufficient, since we are not interested in a complete cluster membership, but rather in the average bulk motions and positions of the youngest stellar cloud members.

Appendix B: Coordinate system definitions and LSR conversion

For completeness, we list the parameters that we used to determine the position and motion of the Sun within the Milky Way in Table B.1. Generally, we use the default values as used by Astropy 4.6. These values are the basis to convert to Galactocentric Cartesian coordinates or to velocities relative to the local standard of rest (LSR).

In this section we also highlight issues that come with erroneously converted values, especially concerning galactic radial velocities, which are given in v LSR in the literature. When investigating gas kinematics as determined by emission line surveys, the gas radial velocity is given by all authors relative to LSR. However, it is often not clear which definitions for the standard solar motion were used in individual studies (i.e., conversion from v HEL to v LSR). This introduces an additional uncertainty and a direct comparison of independent observations can not be done at face value, which was already pointed out in Hacar et al. (2016b). On top of that, when comparing stellar kinematics with gas kinematics, one has to convert the stellar v HEL to v LSR, or vice-versa for the gas. Using a different LSR conversion method for one of these data sets could lead to wrong interpretations. For example, this could introduce an artificial radial velocity shift between two observations, or it could even hide a shift that would be observable otherwise.

In Table B.1 we include the Galactic Cartesian components for three standard solar motions that are relevant for our work. One of the first widely used standard solar motions is given in Mihalas & Binney (1981) with 16.6 km/s. Since the mid 80’s the standard solar motion of 20 km/s, reported in KL86, seems to be common. In the late 90’s Dehnen & Binney (1998) defined a new value (13 km/s) with a significantly lower V component. Today, the most widely used standard was defined by Schönrich et al. (2010), with V⊙ = 18 km/s, which is used also in our work. Beside the values listed here, there are about 15 further published values, for example, discussed in Francis & Anderson (2009). This makes it clear how difficult it is to unambiguously interpret gas velocities. We find that if converting gas velocities v HEL in Orion back to v HEL with different LSR definitions, this could lead to variations of up to 5 km/s or even more. Hence, if the original conversion method is unknown this introduces an additional significant error. For our extracted data, concerning the Nishimura et al. (2015, for Orion A, Orion B), Kun et al. (2008, for L1622), Maddalena et al. (1986, for L1616), and Kun et al. (2001, for IC2118) emission line surveys, we add an additional error of 1 km/s on top of the reported errors for the scatter. Finally, we like to point out that this additional uncertainty — due to wrongly chosen LSR conversion — is not significant enough to change the main outcome of this paper. The relative radial motions of the studied clouds persist even when using different standard solar motions for the conversions.
Table B.1. Properties of the Sun relative to the Galactic center, as used by \textit{Astropy 4.0}.

| Description                                                                 | Values                                                                 | Ref. |
|----------------------------------------------------------------------------|------------------------------------------------------------------------|------|
| Galactocentric Frame (ICRS)                                               | \((\alpha_{\text{GC}}, \delta_{\text{GC}}) = (266.4051, -28.936175)\) deg | 1    |
| Galactocentric distance of Sun                                            | \(d_\odot = 8.122\) kpc                                              | 2    |
| Distance of Sun to Galactic mid-plane                                     | \(Z_\odot = 20.8\) pc                                                | 3    |
| Solar velocity in Galactocentric cylindrical coordinates                 | \((v_{R,\odot}, v_{\phi,\odot}, v_{Z,\odot}) = (-12.9, 245.6, 7.78)\) km/s | 4, 1, 2 |
| LSR motion in Galactocentric cylindrical coordinates                     | \((v_{R,\text{LSR}}, v_{\phi,\text{LSR}}, v_{Z,\text{LSR}}) = (1.8, 233.4, 0.53)\) km/s | 4    |
| Barycentric standard solar motion relative to LSR since 2010              | \((U, V, W) = (11.1, 12.24, 7.25)\) km/s                              | 5    |
| Barycentric standard solar motion relative to LSR since 1986\(^a\)       | \((U, V, W) = (10.0, 15.4, 7.8)\) km/s                                | 6    |
| Barycentric standard solar motion relative to LSR since 1981\(^b\)       | \((U, V, W) = (9.2, 12.0, 6.9)\) km/s                                 | 7    |

**Notes.** \(^a\) The standard solar motion of 20 km/s toward \(l = 56^\circ, b = 23^\circ\) (RA = 18 h, Dec = 30\(^\circ\), epoch 1900) is often used by radio observatories to convert gas radial velocities, as derived from molecular line observations, from \(v_{\text{HEL}}\) to \(v_{\text{LSR}}\), and is given here for completeness (not used by \textit{Astropy 4.0}). \(^b\) This standard solar motion of 16.6 km/s was likely used by Madalena et al. (1986) and is given here for completeness (not used by \textit{Astropy 4.0}).

**References.** (1) Reid & Brunthaler (2004); (2) Gravity Collaboration et al. (2018); (3) Bennett & Bovy (2019); (4) Drimmel & Poggio (2018); (5) Schönrich et al. (2010); (6) Kerr & Lynden-Bell (1986); (7) Mihalas & Binney (1981).