A gravitational and dynamical model of star formation in Orion

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ABSTRACT

The Orion Nebula Cluster (ONC) is the most massive region of active star formation within a kpc of the Sun. Using Gaia EDR3 parallaxes and proper motions, we examine the bulk motions of stars radially and tangentially relative to the cluster center. We find an age gradient with distance to the stars in the ONC, from 385 pc for the oldest stars, to 395 pc for the younger stars, indicating that the star forming front is propagating into the cloud. We find an organized signature of rotation of the central cluster, but it is present only in stars younger than 2 Myr. We also observe a net infall of young stars into the center of the ONC’s deep gravitational potential well. The infalling sources lie preferentially along the filament, on the other hand, outflowing sources are distributed spherically around the cluster, and they have larger velocity dispersion. We further propose a solution to a long-standing question of why the ONC shows a weak signature of expansion even though the cluster is likely bound: much of this expansion is likely driven by unstable N-body interactions among stars, resulting in low-velocity ejections. Finally we observe a significant infall of stars in various low-mass star-forming regions towards the Orion Complex at distances as far away as 200 pc, presumably due to a strong gravitational potential of Orion. Though analyzing signatures imprinted on stellar dynamics across different spatial scales, these observation shed new light on the signatures of formation and evolution of young clusters.

Keywords: Young star clusters, Star forming regions, Interstellar dynamics, N-body problem, Gravitational fields

1. INTRODUCTION

The gravitational fields of star-forming molecular clouds can influence the dynamics of both stars and gas over significant spatial scales. In the solar neighborhood, the most massive of these star forming regions is the Orion Complex. The molecular gas mass of the Orion A and B clouds is $\sim 2 \times 10^5 M_\odot$ (Wilson et al. 2005). The the latest census of young star members in the region shows $> 10^4$ stars (Kounkel & Covey 2019) in a structure that spans $\sim 200$ pc, of which there are a number of OB stars.

In addition to considering the entire Orion Complex, within it there are number of clusters in which density of stars is concentrated; the most massive of these clusters is the Orion Nebula (ONC), which alone contains well over 3000 stars within the radius $\sim 20$ pc of each other, of which $\sim 1000$ are concentrated within a radius of $\sim 2$ pc within the Trapezium (e.g., McBride & Kounkel 2019).

Despite the masses and densities in concentration of stars, so far there have been only a few significant signatures of gravitational pull of the young populations on their surroundings. In particular, $\sigma$ Ori cluster appears to be attracted to the Orion B molecular cloud, whereas Orion B itself (as well as some of the smaller outlying populations) appear to be on the infalling trajectories towards the center of the Orion Complex (Kounkel et al. 2018). However, these are only a few isolated cases, and it is difficult to infer any particular trend for it. On the contrary, most of the Orion Complex appears to expand with speeds in excess of 6 km s$^{-1}$, due to recent turbulence injection from the feedback of massive stars and supernovae (Kounkel 2020; Großschedl et al. 2020; Ha et al. 2021). On more compact level, Kuhn et al. (2019) have analyzed a sample of 28 young clusters; they found that almost none of them appear to have rotational support, and most of them show a preference of expansion.
with a typical velocity of $\sim 0.5 \text{ km s}^{-1}$. Only two clusters, M17 and NGC 6231, have shown some signature of contraction, albeit at a low level of significance. Most importantly, when examining multiple subclusters that are all part of the same population strung together along a filament, they found only a little evidence of convergent motion within them, concluding that they are not involved in a hierarchical assembly that would collect smaller star clumps into a larger cluster.

Over the years, much of the efforts over years have been concentrated on the dynamical state of the ONC based on its proper motions, however the focus has been aimed almost exclusively on the central cluster within it, rather than the full “head” of the Orion A molecular cloud. Early work with motions of stars measured from the photographic plates by Jones & Walker (1988) have concluded that the cluster is most likely not in virial equilibrium, but, as the escape velocity they estimated is comparable or smaller than the velocity dispersion they measured, they considered the cluster to be only weakly bound. Hillenbrand & Hartmann (1998) were able fit the spatial distribution of the stars in the ONC well using the King model profile, and they have argued that while the entire cluster may not necessarily be relaxed, its core is expected to be. They found that the stellar mass within the cluster is only 40% of what is expected for virial equilibrium, but that the remaining gas may account for the remainder, and that it may yet to form a sufficient number of stars for the cluster to remain bound at later stages in its life. Later, Dzib et al. (2017) have used radio interferometry to improve astrometric measurements of stars, and they found no indication of either preferred radial or tangential motion of stars, which would be expected of a virialized population. Finally, since the release of Gaia DR2, several works, such as Kounkel et al. (2018), Kuhn et al. (2019) or Getman et al. (2019) have re-evaluated the dynamics of the ONC, with overall conclusions being that the cluster does appear to be bound, although it may show a weak preference towards expansion, mainly along its outer edges.

In this paper we examine the dynamical state of Orion, the gravitational influence that it has on its vicinity, and the expansion of the stars within it. To clarify the terminology, we refer to the entire “head” as the ONC, and we would frequently use Trapezium to refer to the central cluster core. In Section 2 we present the data used and the general methods of our analysis. Section 3 presents the primary results of our study, first looking at the ONC (Section 3.1) and then the entire Orion Complex as a whole (Section 3.2). In Section 4 we discuss the implications of our findings of an expansion signature in the ONC despite the cluster likely being bound. We conclude with a summary in Section 5.

2. DATA AND METHODS

In this section, we describe the data used and the selection cuts made for our study sample in both the ONC and the larger Orion Complex. We also summarize the basic quantities and conventions adopted in our analysis.

2.1. Data selection
2.1.1. ONC

One of the challenges that the previous works have had in analyzing the dynamical state of the ONC is the sheer number of stars contained within it, as it makes it difficult to fully visualize the velocity vectors of stars. As such, although the cluster appears to be virialized on average, some of the substructure may be less apparent when everything is viewed as a whole. More than that, the ONC contains multiple generations of stars, some younger than 1 Myr, some with ages $> 4$ Myr. While the distributions of these stars of different ages overlap, they do have their own unique features, and this may influence the kinematics as well (Becari et al. 2017). To mitigate both of these issues, we split up the sample of the stars in the ONC based on their age.

The ages of young stars can commonly be determined from placement of their photometry on the HR diagram. However, some confusion can remain regarding the ages of unresolved binary stars which have a higher combined luminosity in comparison to single stars; without taking this into account, the ages that would be inferred photometrically will be underestimated. Although it is still possible to observe trends and gradients in age across given populations (Becari et al. 2017), such age bias can often be difficult to quantify.

Instead we use log $g$ as a proxy for age. As a young star evolves and its radius shrinks, its log $g$ increases until it reaches main sequence. Such measurement is a more direct method of determining an age of a star, as it is significantly less biased by multiplicity. Recently, Olney et al. (2020) have performed analysis of APOGEE spectra to use data-driven techniques to measure calibrated $T_{\text{eff}}$ and log $g$.

We use the spectroscopic sample of stars observed by APOGEE towards the ONC (Kounkel et al. 2018), and following a crossmatch with Gaia EDR3 (Gaia Collaboration et al. 2021), we further restrict it via

- Spatial cuts in RA & Decl. $82 < \alpha < 85^\circ, -6.5 < \delta < -3.5^\circ$
- Cut in parallax $2 < \pi < 3.5$ mas; which translates to a distance cut of 285–500 pc.

We conclude with a summary in Section 5.
• Proper motions within 6 mas yr$^{-1}$ of the mean of the cluster, with the mean motion in the local standard of rest $\mu_\alpha,lsr = 0.8$ mas yr$^{-1}$ and $\mu_\delta,lsr = 2.8$ mas yr$^{-1}$. This translates to a window $\sim$11 km s$^{-1}$ or $\sim$5-6 times the velocity dispersion of the clusters, excluding any fast dynamically ejected runaways such as those in McBride & Koumkel (2019), or the bulk of the potential contamination. The APOGEE sample towards the ONC primarily contains bona-fide members, with only a small fraction of likely field stars, as such, this cut eliminates only 5% of stars.

• Spectroscopically determined $T_{\text{eff}} < 6500$ K and log $g > 3$ dex, restricting the sample to the stars from which spectroscopic ages can be reliably determined.

This produces a sample of 1612 stars, of which 893 are found towards the Trapezium.

While the log $g$ values derived via APOGEE Net do have minor systematic differences relative to various isochrones, such as, e.g., PARSEC (Marigo et al. 2017), we can roughly separate the sample into 5 bins: log $g$ $<$ 3.6 dex ($\lesssim$1 Myr, 125 stars), 3.6 $<$ log $g$ $<$ 3.8 dex (1 $\sim$ 2 Myr, 265 stars), 3.8 $<$ log $g$ $<$ 4.0 dex (2 $\sim$ 3 Myr, 480 stars), 4.0 $<$ log $g$ $<$ 4.2 dex (3 $\sim$ 5 Myr, 445 stars), and 4.2 $<$ log $g$ dex (5 Myr, 297 stars).

2.2. Orion Complex

To examine the effect the Orion Complex has on its surroundings we use the Gaia EDR3 sample from McBride et al. (2020) of low mass young stars. Unlike the older field stars, pre-main sequence stars are dynamically cold with a relatively small velocity dispersion not only within each individual complex, but also as a collective within the Galactic reference frame.

We select only the highest fidelity sources with the classification probability of a star being pre-main sequence of $> 95\%$. We further restrict sources based on age, restricting the sample to those younger than 30 Myr, as well as on distance and proper motions, requiring sources to have $\pi > 2$ mas, and proper motions within 10 mas yr$^{-1}$ of the average for Orion.

To avoid cos$\delta$ projection effect in calculating radial alignment we convert proper motions to the galactic reference frame, in the local standard of rest. Furthermore, we subtract out the Galactic rotation of 220 km $s^{-1}$.

2.2. Analysis

2.2.1. ONC

To examine the motion of stars in the ONC in the reference frame the center of the cluster, we derive a metric representing the relative radial orientation of motion, cos$\theta$, where $\theta$ is defined as

$$\theta = \frac{\tan^{-1}(\mu_\delta,lsr - \mu_\delta,\text{COM,lsr})}{\tan^{-1}(\mu_\delta,lsr - \mu_\delta,\text{COM,lsr})}$$

where $\alpha$ and $\delta$ are the right ascension and declination (in decimal degrees) of the star in question, $\mu_\alpha,lsr$ and $\mu_\delta,lsr$ are the star’s proper motions in right ascension and declination with respect to the local standard of rest ($\text{Schönrich et al. 2010}$), expressed in milliarcseconds per year, $\alpha_{\text{COM}}$ and $\delta_{\text{COM}}$ are the right ascension and declination of the ONC’s center of mass ($\alpha_{\text{COM}} = 83.8^\circ$ and $\delta_{\text{COM}} = -5.4^\circ$), and $\mu_\alpha,\text{COM,lsr}$ and $\mu_\delta,\text{COM,lsr}$ are the mean proper motions of ONC members in right ascension and declination with respect to the local standard of rest ($\mu_{\alpha,\text{COM,lsr}} = 0.8$ mas yr$^{-1}$ and $\mu_{\delta,\text{COM,lsr}} = 2.8$ mas yr$^{-1}$).

We then segregate the selected members of the ONC into three categories based on their computed cos$\theta$ values: cos$\theta > 0.5$ are the sources that are preferentially moving away from the cluster center (566 stars), cos$\theta < -0.5$ are those moving towards the cluster center (440 stars), and $-0.5 < \cos\theta < 0.5$ are those moving tangentially around the cluster/rotating around it (234 stars). The latter sources can be further subdivided through tangential orientation, with sin$\theta < 0$ as the sources preferentially moving clockwise (206 stars), and sin$\theta > 0$ as those moving counterclockwise (206 stars).

2.2.2. Orion Complex

We evaluate the orientation the stars have relative to the average defined in Sec. 2.1.2 in a manner similar to the Equation 1, but converted to the Galactic reference frame. We assume the average position of the Orion Complex to be $l_{\text{COM}} = 205^\circ$, $b_{\text{COM}} = -18^\circ$, and its typical proper motion to be $\mu_\alpha = -1.4$ mas yr$^{-1}$, $\mu_\delta = 0.7$ mas yr$^{-1}$, where $\mu_\alpha$ and $\mu_\delta$ are proper motions in local standard of rest, with galactic rotation subtracted (Bovy 2015).

3. RESULTS

3.1. ONC

As a comparison, we generated a random sample of proper motions for all of the stars in the ONC, drawing both $\mu_\alpha$ and $\mu_\delta$ from the $0.9 \times 1.1$ mas yr$^{-1}$ Gaussian velocity dispersion of the cluster, preserving the positions of each star. We processed these synthetic velocities in a similar manner, and applied similar cuts. We find that in a purely randomly drawn velocities, there is expected...
to be an approximately equal number of infalling, outflowing, and rotating stars. In comparison, real data for the entire ONC shows that the fraction of sources that are rotating is suppressed, and, instead, there is an excess in the number of stars that are infalling (Figure 1). Furthermore, zooming in only on the central cluster, within 0.4° of the cluster center, we find there to be a slight deficit in the expected fraction of the rotating and infalling stars, and instead there is an excess in the number of the stars expanding outwards from the center.

3.1.1. Infall

Figures 2 and 3 show the motions of infalling, expanding, and rotating sources in each of the five age bins. The stars in the oldest age bin (\( \gtrsim 5 \) Myr) predate the formation of the central cluster as a whole. Although there are stars that fall into various cuts of \( \cos \theta \), there is no organized expansion or rotation to speak of, they appear to primarily trace random motions of stars.

However, at the oldest (\( \gtrsim 5 \) Myr) age bin, there does appear to be a significant infall of stars moving towards the Trapezium from south of the ONC, in the vicinity of NGC 1980 (we note that each panel shows the current proper motions of the stars of that age, not necessarily the motions at the time of their formation). This infall becomes even more prominent in the next age bin (3–5 Myr); furthermore, there does appear to be significant infall from north the northern part of the ONC, NGC 1977. This infall continues to persist in the younger age bins as well, until the density of sources. The infalling sources constitute the bulk of sources found north and south of the Trapezium, however, there are next to no infalling sources from either east or west of it (Figure 4, top row). This shows that the filament that has produced the ONC is contracting due to the gravitational potential of both the Trapezium and the entire cluster as a whole.

In contrast, if we examine the sample with randomly generated proper motions, (Figure 4, bottom), the distribution of sources that would have orientation of their proper motions suggestive of either infall, outflow, or rotation are expected to be more homogeneous and uniform across the cluster. Comparing the fraction of stars that are infalling per healpix in the real data vs the random sample via a two-sided Kolmogorov-Smirnov test shows that the two populations are distinct at \( \gtrsim 4 \sigma \) level. The difference becomes more pronounced when segregating the ONC into 3 portions: the top (\( \delta \gtrsim -5^\circ \)), middle (-5.8° \( \lesssim \delta \lesssim -5^\circ \)), and bottom (\( \delta \lesssim -5.8^\circ \)). The resulting KS-test statistics are shown in Table 1.

3.1.2. Expansion

Stars with age \( < 5 \) Myr begin to trace the central overdensity associated with the Trapezium, and the younger they are, the more centrally concentrated they become. Around the cluster core (including along the OMC 2/3 filament), there is little to no organized infall of stars towards the center. However, as soon as the central cluster begins to develop, there is a significant signature of both rotation and expansion. The bulk of the expanding sources can be traced back directly to the cluster center and they tend to be distributed spherically around it. However, the expanding sources dominate the sample around the outer edges on the east and the west side of the cluster due to this spherical distribution, as there is no overlap with the infalling sources that are only found along the filament (Figure 4). That preference for the outer edges of the cluster to be dominated by expansion has previously been noted by Kounkel et al. (2018), Kuhn et al. (2019), and Getman et al. (2019).

3.1.3. Rotation

Examining the rotation around the Trapezium, within 0.4° of the cluster center, in sources that are preferentially moving tangentially, there is little to no preference in the direction among the stars that are older than 2 Myr. However, there is a strong preference for clockwise motion in younger stars, by a factor of \( \sim 2 \) among 1–2 Myr old stars, and by a factor of \( \sim 3 \) among \( < 1 \) Myr old stars (Figure 5). It is difficult to say, however, if the older stars used to have a preferred orientation that has since been washed out over their lifetime through the dynamical evolution of the cluster, with the younger stars being the only ones with some memory of it, or if the angular momentum of the cluster has evolved over time as the cluster grew in such a manner as to develop a semi-coherent rotation only for the currently forming stars.

Rotation of the molecular gas in ONC has been previously predicted in the toy model of the formation of the cluster from Hartmann & Burkert (2007), and it is expected that the stars would inherit the angular momentum from the gas. A weak signature of rotation of
the central cluster has also been reported by Theissen et al. (2021).

Among the youngest (<1 Myr) sources that are rotating around the cluster center, the angular momentum appears to be conserved, with tangential velocity inversely proportional to the radius at which these stars are found (Figure 6). From this constant $r \times v_{\text{rot}}$, it is possible to estimate the specific angular momentum of $\sim 7.4 \times 10^{20}$ cm$^2$ s$^{-1}$, with both $r$ and $v$ being 2d projections in the plane of the sky of these youngest sources rotating around the cluster. This specific angular momentum is a factor of $\sim 1.8$ higher than the specific angular momentum of the Orion B molecular cloud (Hsieh et al. 2021). However, in the older stars (including 1–2 Myr), the coherence between $v_{\text{rot}}$ and $r$ is no longer apparent, that is to say, $v$ has a significant scatter relative to $r$ which washes away any trends.

### 3.1.4. Radial velocity component

Examining the distribution of the stars in the ONC in the plane of the sky and their proper motions allows for an incredible precision in inferring the dynamical state of the cluster, however, some leverage can be also gained via examining distance of the stars and the radial velocity. However, as even with Gaia EDR3, parallaxes can be very uncertain, resulting in a large spread in the inferred distance, we limit the sample only to the sources with $\sigma_\pi < 0.04$ mas, which, at the distance of the ONC translates to $\sim 6$ pc, which is still considerable, as it is comparable to the size of the cluster in the plane of the sky, but, nonetheless, allows to resolve some structure along the line of sight. However, imposing this constraint on $\sigma_\pi$ significantly limits the sample to only 533 stars, particularly towards the central cluster due to large degree of nebulosity in the region degrading the quality of the parallaxes.

We examine the distance versus the vertical extent of the cluster in $\delta$ converted to physical units in Figure 7, highlighting the velocities of the sources in these two respective dimensions. The assignment of infalling and outflowing sources is retained from the previous figures based on their plane of the sky velocities. On a first glance, the outflowing sources in this plane appear to be somewhat different than in Figure 2; we note that this is primarily due to the strict $\sigma_\pi$ cut preferentially excluding sources in the region where expansion is most strongly apparent.

When examining the full sample of infalling and outflowing sources only in the radial velocity space, where the cut on parallax quality is not necessary, we find that the stars that are infalling have a good agreement with RVs of the gas along all $\delta$ in the cluster. On the other hand, the outflowing stars not only often have a larger velocity dispersion (Table 2), they also may be offset from the gas. This is most strongly apparent at $\delta \sim -5^\circ$ where the peak of the RV distribution of outflowing stars is blueshifted relative to the gas. The origin of this blueshifted stellar component has long since been questioned (Fürész et al. 2008; Tobin et al. 2009; Kounkel et al. 2016). We can finally offer a partial explanation: radial velocities of these stars could have been dynamically processed by the central cluster. The mean velocity of the expanding stars is more comparable to the mean velocity of the central cluster, on the other hand the gas north of the cluster is intrinsically redshifted. As such, the total distribution of the stars formed from the molecular gas in that region coupled with the stars that most likely originate in the central cluster but since
Proper motions of stars towards ONC, separated into 5 age bins, shown in separate rows, based on their log g, with the velocity vectors color-coded based on the orientation relative to the center: red for infall, blue for expansion, magenta for clockwise rotation, green for counter-clockwise rotation. The length of each vector corresponds to the motion of a star over the next 0.2 Myr. Typical velocities are 1.2 mas yr\(^{-1}\), or 2.2 km s\(^{-1}\). The black dot shows the assumed center of the cluster. The first column shows the full sample, second column - only the sources that are falling towards the center, third column - only the sources outflowing from the center, fourth - sources that are preferentially moving tangentially around the center.
Figure 3. Same as Figure 2, but zoomed in on Trapezium. The length of the vectors is decreased to the distance covered in 0.1 Myr.
Figure 4. Top: Map of the ONC showing fraction of sources in a given healpix that are preferentially falling into the center of the ONC, expanding outwards, and those that are preferentially moving tangentially around it. Bottom: same as above, but the velocities for each star have been generated randomly from a Gaussian distribution representing the cluster, to highlight the differences between the real data and the null hypothesis.

| Table 2. Radial velocity statistics |
|------------------------------------|
|                                    |
| $v_{\text{med}}$ & $\sigma_v$ & $N_s$ & $\log g$ & $v_{\text{med}}$ & $\sigma_v$ & $N_s$ & $\log g$ & $v_r$ & $\sigma_v$ & $N_s$ & $\log g$ |
|------------------------------------|
| $-4.9 < \delta < -4.5^{\circ}$  |
| 13.4 & 1.4 & 89 & 3.97 & 11.7 & 3.0 & 63 & 4.09 & 13.1 & 2.0 & 43 & 4.01 |
| $-5.3 < \delta < -4.9^{\circ}$  |
| 12.3 & 1.8 & 111 & 3.90 & 10.5 & 2.7 & 155 & 3.94 & 11.4 & 2.6 & 77 & 3.90 |
| $-5.7 < \delta < -5.3^{\circ}$  |
| 9.6 & 1.9 & 190 & 3.93 & 10.0 & 3.4 & 258 & 3.90 & 10.0 & 2.2 & 245 & 3.94 |
| $-6.1 < \delta < -5.7^{\circ}$  |
| 9.2 & 1.0 & 139 & 4.12 & 8.6 & 1.6 & 65 & 3.95 & 8.3 & 3.4 & 40 & 4.02 |
| $-6.5 < \delta < -6.1^{\circ}$  |
| 9.6 & 0.9 & 96 & 3.90 & 8.0 & 1.3 & 31 & 3.93 & 7.6 & 2.1 & 45 & 3.93 |

* Mean (lsr) radial velocity and radial velocity dispersion in km s$^{-1}$ fitted as a Gaussian to the RV distribution in the slice, ignoring outlying wide wings.

* Mean $\log g$ of the stars in the slice.
Figure 5. Distribution of direction of motion of sources within 0.4° around the cluster center that preferentially exhibiting tangential motion. Orientation < 0 shows the sources moving clockwise, > 0 are those moving counterclockwise. Sources are separated into 4 age bins.

Figure 6. Tangential velocity as a function of radial distance of the stars with age <1 Myr that are preferentially rotating around the cluster center. The fitted blue line follows the relation of $v = 2/r$.

These populations surround the Orion Complex along different sides, and, regardless of their line of sight, have motions strongly aligned towards Orion.

This is most likely due to the gravitational potential of the Complex. However, it may also be partially due to the initial velocity field that has allowed the assembly of the Orion Complex in the first place, as the “infall” and “inflow” of stars may be difficult to conclusively separate. Nonetheless, given for a significant coherence in proper motions both in the populations from the East and from the West to concentrate towards Orion, it is difficult to imagine a scenario in which the Orion Complex and the velocity field of young stars around it are decoupled. Rather, the question is: is everything moving towards Orion because it is so massive, or is Orion so massive because everything was moving towards it in the first place, such as, e.g., due to some converging flows from older supernova bubbles?

The true magnitude of acceleration solely due to gravity may be difficult to measure, as each population would have its own non-zero peculiar velocity had a population as massive as Orion not have been there (See Section 4.4.2 for discussion of various effects including the Galactic potential). More massive populations, particularly those further removed, such as Vela and Perseus, do not appear to be strongly affected. On the other hand more nearby and less massive, more diffuse populations, find all of their velocity vectors strongly converge towards Orion. The populations of young stars between Orion and Vela in particular have a gradient in the proper motions with the trajectory: the closer the young stars are to Orion, the more those stars’ velocities appear to be affected.

4. DISCUSSION

4.1. Boundedness of the ONC

Given that the central cluster in the ONC has a substantially large self-gravity to attract other parts of the filament, it would be difficult to imagine the cluster itself being unbound, with the stars merely drifting off due to a lack of sufficiently strong gravitational potential that would hold them together. Rather, it is likely that a large fraction of the expanding sources have been ejected through N-body interactions, either in unstable triple systems, or through chance encounters of a binary with another star in the cluster in close proximity. It may be difficult to fully disentangle which stars have been ejected, and which stars have proper motions that only coincidentally appear to point away from the cluster center. However, stars that are outside of the inner-most cluster core, stars that are found in the parameter space not balanced by an equal number of infalling stars,
Figure 7. Same as Figure 2, but showing distance from the Sun versus the position along the filament in $\delta$ converted to physical units, with vectors converted from the $\mu_\delta$ and radial velocities. The length of the vectors corresponds to the distance covered in 0.4 Myr. Typical uncertainties in distance are $\sim$6 pc.
Figure 8. Radial velocity of the $^{13}$CO molecular gas (Bally et al. 1987), and that of the stars in the sample, in the local standard of rest reference frame. Left panel shows the full view of the cluster, right panel is binned in 5 discrete slices along $\delta$. The velocity distribution of the gas is shown in greyscale in the background of the left panel, and as a black line in each tier of the panel on the right. Infalling and outflowing stars are shown in red and blue respectively. On the right each distribution is scaled relative to its peak.
stars that project back directly to the center without any angular offset are particularly likely candidates of bona fide orphans from a past ejection.

In dynamical simulations, the mean ejection velocity of the unstable N-body interactions is 2.8 km s$^{-1}$ which later decays to 1.1 km s$^{-1}$ through intracluster interactions (Reipurth et al. 2008). This is similar to the typical velocity of the stars that are expanding away that we observe. Comparatively, true high velocity walkaway and runaway stars are rare, though, there are several dozen that are currently known to be associated with the ONC (McBride & Kounkel 2019; Schoettler et al. 2020; Farias et al. 2020). As such, hundreds of stars with lower ejection velocity are expected. As we have deliberately cut the amplitude of the proper motions to exclude high velocity stars that could be considered as runaways, the bulk of these expanding stars may still remain gravitationally bound to the cluster, and they would be forced to turn around as they climb out the potential well. The primary reason why so many could be detected can be attributed to the youth of these stars and the recency of their ejection.

Almost all of the expanding stars (~94%) have traceback ages that are smaller than the age assigned to a star based on their log $g$. This is to be expected, as it would be impossible to eject them from the central cluster otherwise. Interestingly, the candidate ejected stars in the younger age bins appear to have a larger high velocity (>4 km s$^{-1}$) tail in comparison to their older counterparts (Figure 2, third column). As the catalog on which this analysis is performed consists of sources that have been targeted for spectroscopic observations, older stars moving with comparable speeds are likely to be out of bounds of the targeted area, assuming they were ejected shortly after their formation.

Virial equilibrium generally assumes that the system has been able to stabilize over time. Young star forming regions, however, can be rather chaotic. The ONC, in particular, is still forming stars. A substantial fraction of those stars may be high order multiple systems (12% of field stars are multiples of at least 3 or more stars, Raghavan et al. 2010), and they would not necessarily have a stable configuration when they form. Similarly, a formation of a binary star, or even a star without a companion, may upset the virial equilibrium of a young dense cluster, if they wander too close to another system and eject one of the stars. A sufficiently large number of such events, even if they have a low ejection velocity, may increase velocity dispersion of the cluster and result in its apparent expansion. Virial parameter (Bertoldi & McKee 1992) is often used to test boundness of a cluster, but it is difficult to measure and requires a number of assumptions, from the total mass of a cluster, to the geometry of the potential, to the symmetry in the velocity dispersion, etc. Such ejection effects could further muddle the fundamental assumptions behind such cal-

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Figure 9. Proper motions of young stars in the solar neighborhood in vicinity of the Orion Complex, color coded by the direction of the velocity vectors relative to the average of Orion, with red corresponding to the motion towards Orion, and blue is the direction away from the center of the Complex. Velocity has been corrected for the local standard of rest and the galactic rotation. The length of each vector corresponds to the motion of stars over the next 1 Myr. The scale bar of $30^\circ$ roughly corresponds to a separation of~150 pc at the typical distances.
4.2. Distance to the ONC and receding star formation

Previously there has been some contention regarding the orientation of the ONC’s parent filament in the plane of the sky: Kounkel et al. (2018) and Großschedl et al. (2018) found it to be largely flat, with a near-constant distance across its length, whereas Stutz et al. (2018) and (Getman et al. 2019) found a significant variation in distance, with the central cluster being found at a larger distance than everything else in the ONC.

Separating the sources into different age bins based on their log g does show a peculiar trend in Figure 7: the distance to the ONC does not appear to be constant as a function of age. Figure 10 shows the interpolated distance of the stars at each age bin, and it accentuates the variance in distance further. The oldest stars tend to be the closest, at the distance of ~385 pc. The younger (1–2 Myr) stars are further away, at ~395 pc. This appears to hold true across the entire filament, although given that younger stars are far more numerous in the Trapezium than elsewhere, this could result in the apparent asymmetry that Getman et al. (2019) has observed. On the other hand, if the sample selection is less sensitive to the youngest stars, this could produce a more uniform distance distribution as in Kounkel et al. (2018) and Großschedl et al. (2018).

We note that stars with age < 1 Myr may appear to break this trend of receding star formation, their average distance appears to be centered on 390 pc, closer than stars in 1–2 Myr age bin (Figure 7). However, as they are most likely to be heavily extinguished, (both due to being still embedded within the envelope of gas and due to having a protoplanetary disk, many without any optical emission), imposing strict parallax quality cuts, with σ_π depending on G flux, may result in their census being particularly biased to sources sitting towards the front of the cloud.

The overall progression of distances from 5 Myr stars to 1 Myr stars itself is unlikely to be attributable to such a bias. Older stars tend to have somewhat lower luminosity (by ∼0.5 mag) due to having smaller radii, however the difference in the distance modulus between 385 and 395 pc is negligible (0.05 mag). Even considering the difference in extinction increasing with distance traveling through the cloud, it is difficult to explain older and younger stars not necessarily being co-located.

The stars (particularly those that are infalling, regardless of their age) tend to share a common radial velocity with the gas. However, if older stars are physically separated from the younger stars that are currently being formed, this implies that the bulk of the ONC is not necessarily co-located with molecular gas, with stars sitting in front of the reservoir of gas. Indeed, a 3-d model of ionized gas of the nebula assumes that even the central cluster is located in front of the cloud (O’dell 2001).

This, combined with gravitational infall (which has also been previously observed by Getman et al. 2019), can in part explain the peculiar RV structure in the ONC towards NGC 1977 (δ ∼ −4.9°). The RVs towards it are not only more red-shifted than what is found in the south of the cluster, the stellar RVs (of the infalling stars^1) are also somewhat more redshifted than the gas. Various scenarios for its motions have been considered by Getman et al. (2019). However, this is likely a signature of gravitational infall, sources in NGC 1977 being attracted to the younger stars in the central cluster that are located further away. This is similar to the scenario considered by Tobin et al. (2009) and Proszkow et al. (2009).

Similarly, Hacar et al. (2017) have observed a blue-shifted “wedge” in the N$_2$H+ gas in the inner 1 pc within the central cluster that is less apparent in the more diffuse CO gas. The fresh dense molecular gas that is sitting behind the cluster can nonetheless feel gravitational attraction to the cluster, and it is also infalling as it is pulled towards it.

4.3. Combined model of the star forming history of the ONC

^1 As previously mentioned, the velocities of the outflowing stars in that region most likely have been dynamically processed since their formation, as such they may not be representative of the primordial kinematics in the region.
Figure 11. A conceptual model showing a side view of the Orion A molecular cloud (corresponding to distance vs \( \delta \) projection), and the relation of ONC relative to it. The cluster shows the age gradient with distance, with the younger stars located closer to the cloud; direction of star formation propagation is indicated by a yellow arrow. Meanwhile, northern and southern part of the cluster are contracting towards the central cluster, indicated by black arrows.

It has been previously noted by Kounkel et al. (2020) and Großschedl et al. (2020) that 6 Myr ago a supernova (or several supernovae) have triggered the global expansion of the Orion Complex. Given that the ONC is being pushed into the Orion A molecular cloud (Großschedl et al. 2018) from the direction of the center of the expansion, it is likely that the shockwave from a supernova has swept along the gas through the filamentary cloud, compressing the gas, and jump-starting the formation of the cluster.

This shock-driven star formation scenario can account for the variable distance to the ONC as a function of age. If the shockwave is propagating into the cloud at a slightly faster rate (faster by \( \sim 2 \text{ km s}^{-1} \)) than the typical radial velocity of the gas and the stars, this would displace the star forming front. Such propagation velocity is comparable to the sound speed in the ONC (Goicoechea et al. 2015).

Early on, star formation has occurred all throughout the length of the filament at an equal rate, but, eventually, as the cluster grew more and more massive, self-gravity became more important. The molecular gas was pulled increasingly more towards the middle, forming the central cluster, even though the bulk of the stars in the central cluster were formed further away than the initial burst of star formation in the region. As the star forming front of the ONC was being pushed into the Orion A molecular cloud (Figure 11) and continuing to access fresh gas, this provided sufficient fuel to form multiple generations of stars in the central cluster, increasing its mass and gravitational pull. On the other hand, NGC 1980 to the south and NGC 1977 to the north of it could not sustain star formation beyond the initial burst. To various degree, the molecular gas that was originally there was a) consumed in forming stars, b) attracted towards the central cluster, and c) dissipated through stellar feedback. They could not replenish their gas content with Trapezium hoarding all of the new material.

Getman et al. (2019) have noted that the more distant stars in the ONC are receding from the observer at a slower rate than the closer parts of the cluster. This does appear to be the case of the entire population, particularly due to NGC 1977. However, this distance-velocity relation is not immediately apparent in the RV distributions of stars segregated into different age bins along a given line of sight. Nonetheless, this may be a signature of either the shockwave slowing down as it is encountering more and more gas of the filament, or the self-gravity of the ONC is protesting against the sheering of the spatially differential star formation and is attempting to bring the older nearby stars and younger distant stars closer together.

4.4. Order of magnitude mass estimates

4.4.1. ONC

The sources that are infalling may offer a possible way estimate the dynamical mass of both the ONC and the Orion Complex, however, as has been previously stated, such a calculation is difficult as we do not fully know the initial velocity field that was present in the region beforehand. Similarly, as acceleration changes velocity incrementally over time, it is important to consider the time scales over which the force of gravity affects the surroundings, which is non-trivial to estimate, as the conditions in a star-forming cloud can and do drastically change over time.

However, it is possible to make a rough order of magnitude inference assuming simple conditions to compare the derived mass with what is typically assumed for the population in question.

If we treat ONC as an isolated system and if we assume typical infall velocities of 2 km s\(^{-1}\) at 5 pc, which is a rough order of magnitude of the observed velocities, starting from rest, over \( \sim 3 \) Myr, it would require a cluster mass of 2,500 M\(_{\odot}\) to achieve such an acceleration. This is well-comparable to the estimate of mass of the ONC from Hillenbrand & Hartmann (1998) of 4,500 M\(_{\odot}\).

4.4.2. The Orion Complex

The earliest stars to form in the Orion Complex have an age of 12 Myr, although the bulk of the region’s star formation occurred 6–8 Myr ago (Kounkel et al. 2018).
The clouds itself could have taken some time to assemble, as such, the relevant time scales could be longer. Nonetheless, if we assume a period of 10 Myr, to accelerate an object located 150 pc from rest to 2 km s$^{-1}$ over this time would require a mass of $6 \times 10^5 \, M_\odot$ — this is most likely an upper limit, and a different approach to assumptions can lower it. The current mass of Orion A & B molecular clouds is considered to be $\sim 2 \times 10^5$ (Wilson et al. 2005); however, Orion A & B is only what is left over of the molecular gas in the Orion Complex, as approximately half of the stars within it are no longer collocated with the molecular gas. As such, although the original mass may be difficult to infer, it is does appear to be similar to this order of magnitude estimate.

However, the Orion Complex is not the only source of mass in the region. Both the mass of the more evolved field stars within a volume of space with 150–200 pc radius, and the potential of the Galaxy are an order of magnitude larger than those of Orion itself (McKee et al. 2015).

To test how effective the Orion Complex can be in dominating the potential in its immediate vicinity in spite of the competing effects, we constructed a toy model using GaiaPy (Bovy 2015). To do that, we have approximated Orion as a Plummer sphere with a mass of $2 \times 10^5 \, M_\odot$, and placed it within the Galactic potential (MWPotential2014). Orion was placed at $X = -330$ pc, $Y = -150$ pc, $Z = -120$ pc in a heliocentric system, which approximates its current location. Its velocity was set as $W = -1.5 \, \text{km s}^{-1}$, moving out of the plane, and $U$ and $V$ were kept at rest at 0 km s$^{-1}$. Orion’s position is allowed to evolve over time as it interacts with the Galactic potential.

We added star test particles, up to 250 pc away from Orion in X and Y, with Z randomized between $-50$–$-120$ pc, i.e., below the plane but somewhat closer to the plane than Orion. Initial velocity of the test particles was set similar to Orion ($U, V = 0 \, \text{km s}^{-1}$, $W = -1.5 \, \text{km s}^{-1}$), as all star forming regions in the solar neighborhood are expanding away from the center of the Local Bubble (McBride et al. 2020).

The system was allowed to evolve for 10 Myr. We then examined the developed position and velocity of the test particles in the reference frame of the Orion Complex. We have also generated a similarly initialized model, but in a purely Galactic potential, without potential of Orion added. In the latter case we still evaluated position and velocity in Orion’s reference frame, to compare how a presence of a massive Complex would affect the velocity field relative to the case without it.

In the model without Orion’s potential, sources along the X axis appear to naturally move outwards, whereas sources along the Y axis appear to move inwards relative to the reference point, forming an X-shaped pattern. On the other hand, adding in Orion’s potential creates a bubble, $\sim 100$ pc in radius, within which sources preferentially fall in towards Orion regardless of where the sources are located in the $X - Y$ plane (Figure 12). There is a slight outflow detected within this bubble: these outflowing sources were originally located close to Orion, and they have “shot through”, exiting on the other side of it.

Similarly, when we examine velocity magnitude of the stars as a function of separation from Orion, we find a significant excess in fast moving stars in comparison to the base model at close separations. Sources within 50 pc appear to be completely dominated by the potential of Orion. Within separations of 50–100 pc, 25% of stars have faster speeds than in the base model. A marginal excess is also observed at separations of 100–200 pc, although significantly less pronounced.

This test assumes the mass of Orion of $2 \times 10^5 \, M_\odot$, to match the current mass of the molecular gas in the region, which is a lower limit of the total mass in the region. Increasing the mass to $6 \times 10^5 \, M_\odot$, to match the higher limit order of magnitude estimate from above, the size of the infalling bubble increases from 100 pc to $> 150$ pc, with a considerable excess in fast moving stars up to $> 200$ pc.

This is a simple toy model that does not have the full complexity of either the morphology of Orion, potential from other nearby star forming regions, or initial conditions of the young stars in Orion’s neighborhood. This model does demonstrate that the presence of mass in Orion over the course of its lifetime can account for the bulk of the observed infalling young stars in nearby star forming regions moving on radial trajectory towards it, even in the presence of the Galactic potential. Nonetheless, the initial conditions are important, as there may have been some initial convergent flows that got imprinted onto the kinematics of the stars, as such it is currently difficult to fully disentangle the two.

In future, with better understanding of the velocity field across the solar neighborhood, supplemented with RVs from all-sky surveys such as SDSS-V, it may be possible to construct a more comprehensive model to better deconstruct the full effect of the relevant dynamical processes in 3d across the entire solar neighborhood.

5. CONCLUSIONS

$^2$ Such outflowing sources may be observed in Figure 9 in the real data at e.g., b $\sim -30^\circ$ as they appear to have different traceback time than the bulk of the expanding sources in the region.
We analyze the dynamics of young stars within the Orion Nebula and the solar neighborhood in the vicinity of the Orion Complex as a whole. We find that

- Examining the orientation of the proper motions of Orion members, we detect a significant (> 4σ) excess of sources whose proper motions are consistent with infall toward the ONC. These infall signatures are most prominent to the north and south of the ONC, within the integral filament where stars are least likely to have been dynamically processed by a passage through the ONC. We interpret this signature as evidence that the stars in and around the ONC are contracting lengthwise along the integral filament, likely due to the self-gravity of the Trapezium.

- We also detect a more modest (∼ 3σ) excess of sources with proper motions consistent with expansion from the ONC; the significance of this excess is largest for sources offset in RA, rather than Dec, from the ONC, placing them outside the integral filament, and thus more likely to be on orbits that have been dynamically processed via interactions in the ONC. We interpret this signature as evidence of dynamical processing of the ONC’s stellar population, not due to the cluster itself being unbound. However, dynamical ejections could inflate the estimate of the virial parameter of a young population, which is a common metric that tests for boundness.

- Among the youngest stars in the ONC that have purely tangential motion, there is a preferred direction of rotation around the central cluster, there is no such preference among the older stars. As such, the angular momentum of the cluster has either evolved to develop organized rotation after the cluster has accreted enough mass, or early sig-

Figure 12. Top left: Projection of position and velocity of stellar test particles in the reference frame of Orion, evolved from rest after 10 Myr in a model consisted of solely Galactic potential. Bottom: Same as previous, but with a moving potential of Orion corresponding to $2 \times 10^5$ M$_\odot$ added to the Galactic potential. Left and right panel were separated to show infalling and outflowing sources, to highlight activity in the center. Note the presence of the bubble extending up to 100 pc within which the stars are preferentially infalling, in comparison to the base model. Top right: comparison of velocity magnitude as a function of the distance from Orion between the base model and the model with Orion’s potential.
natures of organized rotation in older stars has since been washed out through the dynamical evolution.

- The distance to the ONC depends on the age of the sample; it varies from \( \sim 385 \) pc for the oldest stars, to \( \sim 395 \) pc for the younger stars; the star formation is continuously propagating into the Orion A molecular cloud at a faster rate than the typical velocity of the gas and the stars, consuming the outer layers of the gas in the process.

- The Orion Complex as a whole is a massive entity (with \( 2 \times 10^4 \text{ M}_\odot \) as a lower limit, \( 6 \times 10^4 \text{ M}_\odot \) as an upper limit) that appears to attract a number of nearby star forming regions, with its reach extending as far out as \( \sim 200 \) pc, resulting with the stars in those populations having infalling or inflowing trajectories towards it. The effect is primarily limited to the nearby lower mass star forming regions. More massive regions found towards the outer limits of that radius, such as Perseus or Vela, may still feel a gravitational pull from Orion, but the velocities of the stars inside those populations do not appear to be affected as strongly as they do in the lower mass regions.

- The gravitational infall from nearby stellar populations can be reproduced in a a dynamical toy model of the Orion Complex and the Solar Neighborhood.

- These observations reveal that young star forming clusters are highly dynamic entities, and the structure of these clusters as well as velocities of stars within them are affected by various processes occurring across different scales. The ONC is not homogeneous. Its dynamical evolution is influenced in different measure by the gravitational potential of its surroundings, gravitational interactions between the stars, as well as the activity within the rest of the Complex. All these effects leave different kinematical signatures that are difficult to separate when examining the entire cluster as a whole, but they become more apparent through identifying appropriate subsets of stars.

**Software:** TOPCAT (Taylor 2005), GalPy (Bovy 2015)

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